Managing Pacific Salmon for Ecosystem Values:

Ecosystem Indicators and the Wild Salmon Policy

Prepared for the Pacific Fisheries Resource Conservation Council by

**Marc Nelitz, Carol Murray, Marc Porter,
and David R. Marmorek
ESSA Technologies Ltd.**

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EXECUTIVE SUMMARY

Section I—Context

Canada's Wild Salmon Policy (WSP) was released in June 2005 with a goal to restore and maintain healthy and diverse salmon populations and their habitats. Strategy 3, Action Step 3.1 aims to include ecosystem values in decision-making by proposing *"ecosystem indicators"* to monitor the status of freshwater and terrestrial ecosystems. The scientific basis for proposing ecosystem indicators within the WSP recognizes that Pacific salmon play an important role in marine, freshwater, and terrestrial ecosystems, including streams, lakes, riparian forests and wildlife food webs. Managers influence these ecosystems by considering changes in fisheries regulations (i.e., harvest levels) and artificial enhancement (e.g., hatcheries). Thus, the role of ecosystem indicators is to provide a measure of ecosystem responses to changes in spawner abundance, thereby helping managers understand how changes in their actions affect freshwater and terrestrial ecosystems.

This work serves three functions: (1) provide a first attempt at developing ecosystem indicators for Strategy 3 of the Wild Salmon Policy; (2) recommend further development and refinement of ecosystem indicators; and (3) suggest next steps. To serve these functions, we reviewed the literature to develop a *better understanding of the linkages* among the five Pacific salmon species and freshwater / terrestrial ecosystems, and used our resulting summary on the "state of the science" to provide a scientific rationale for *recommending ecosystem indicators* and *next steps*.

Section II—Management Problem

Salmon affect ecosystems in a variety of ways. First, salmon may affect *ecosystem composition*—the other biological, chemical or physical features of stream, lake, and riparian ecosystems. Isotope studies demonstrate that marine-derived nutrients from salmon can be found in riparian vegetation, and wildlife species. Various authors have also inferred ecological effects of salmon nutrient subsidies such as increased carrying capacity of bear populations, increased size of individual bears, and changes in the timing of lactation in mink. Second, salmon may affect *ecosystem structure*—the arrangement of ecosystem components. Some have suggested that increases in spawner abundance increase rates of straying of salmon from their natal streams, thereby enhancing biodiversity via changes in the genetic structure of other salmon stocks. Third, salmon may also affect *ecosystem function*—the natural ecosystem processes of creation and destruction. For instance, salmon act as ecosystem engineers when digging redds. Such physical alterations of a streambed can change water-flow patterns, promote channel migration, alter sediment accumulation, and decrease algal biomass and macroinvertebrate densities. The emphasis of this report is to understand the effects of salmon on ecosystem composition—the role of *spawners*, *carcasses*, and to a lesser extent *eggs*, in contributing to *nutrient* and *food* budgets in freshwater (streams and lakes) and terrestrial (riparian vegetation and wildlife) ecosystems.

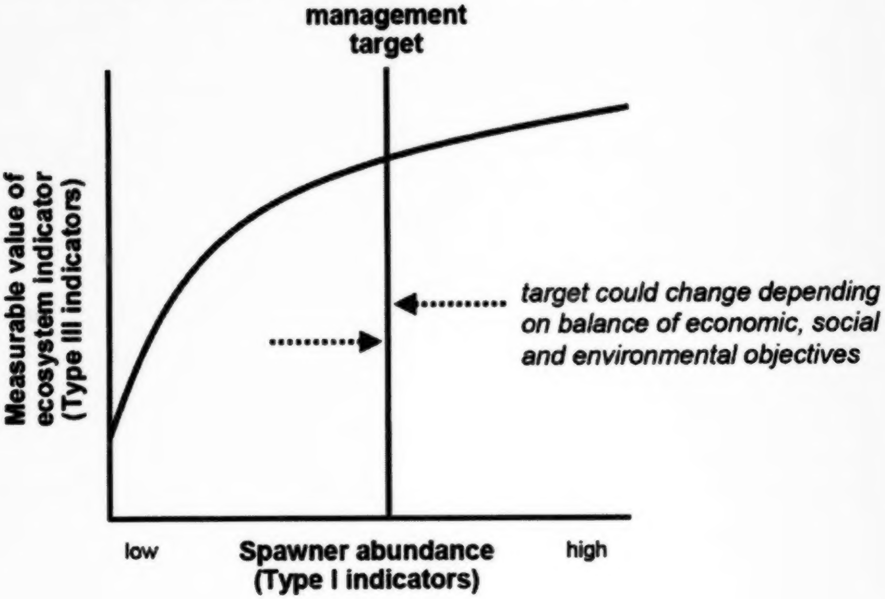
Ecosystem indicators are intended to bridge the gap between science and decision-making. The role of science-based indicators can be illustrated using Figure E1, where the x-axis represents spawner abundance and the y-axis represents a measurable value for an ecosystem indicator of interest (e.g., changes in macroinvertebrate biomass). The relationship between these two variables is represented by a non-linear curve. Managers affect freshwater ecosystems by changing harvest rates. For example, changes in spawner abundance (points along the x-axis) will correspond to a related change in some measurable attribute of the ecosystem (point along the y-axis).

This conceptual framework is useful for clarifying Strategy 3 of the Wild Salmon Policy, by helping managers and scientists:

1. Identify the ecosystem values, objectives and indicators—i.e., what are the variables of interest on the y-axis?
2. Decide upon a suitable range of responses within which to maintain an ecosystem indicator—i.e., what is a suitable range of values along the y-axis within which to manage an ecosystem?
3. Determine sufficient levels of escapement to maintain ecosystem responses of interest within the preferred "zones" of response—i.e., what are some target levels of escapement which will meet ecosystem objectives?

Figure E1. Hypothetical relationship between spawner abundance and an ecosystem indicator of interest.

Solid vertical line indicates a point along the x axis at which a manager may set some target escapement based on achieving one of a variety of goals (e.g., optimum harvest or conservation).



Section III—Approach to Identifying Indicators

Articulating management challenges in the form of questions that affect decisions is an effective approach for prioritizing information and monitoring needs. Monitoring programs that are not well thought through will not provide information that is most relevant to managers. Hence, we have identified three questions that relate to monitoring and indicator needs under Strategy 3 of the Wild Salmon Policy, and grouped the indicators accordingly.

Type I indicators are intended to help answer the question, *"Which factors affect spawner abundance?"* Both human factors (changes in harvest) and natural factors (changes in marine conditions and enroute mortality) affect the number of spawners returning to natal streams—i.e., location along the x-axis in Figure E1. Managers need to know that their actions are actually having their intended effects both on achieved escapement levels and on the ecosystem, rather than outcomes being the result of some confounding factor which is naturally driving changes in escapement.

Type II indicators are intended to answer the question, "*In which areas will increases in spawner abundance have the greatest influence on other ecosystem values?*" Salmon contribute important marine subsidies of food and nutrients to freshwater environments. However, not all watersheds are equally reliant on these subsidies (i.e., some are not nutrient limited). Managers will want to identify high priority areas that are nutrient or food limited, such that increasing numbers of spawners will most likely have the greatest positive effect on freshwater, riparian, or terrestrial ecosystems. These areas will include watersheds that are either currently or historically known to have supported salmon. This will help salmon managers both maintain ecosystem conditions in areas where salmon provide important contributions today, and attempt to restore conditions in locations where salmon were historically more abundant.

Type III indicators will ultimately help managers understand the response of an ecosystem indicator to their actions by asking, "*How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems?*". Ecosystem responses may take a variety of forms and it is not clear how any one indicator will respond in a particular watershed. Managers will need to consider tradeoffs among the various indicators when setting management targets because the direction and magnitude of change (positive or negative) may vary with each indicator. In other words, no single target will maximize all environmental, social and economic objectives.

Section IV—Recommended Indicator Themes and Candidate Indicators

The recommended indicator themes and candidate indicators (Table E1) are those that we think will best answer the three key questions, described above. Indicator themes may: (1) be important direct or indirect drivers of ecosystem responses (e.g., marine conditions affect salmon abundance); (2) help understand the effect of potentially confounding influences on ecosystem response (e.g., the role of agriculture, forestry, or waste management activities in masking the effect of nutrient contributions of salmon); or (3) provide direct measures of the linkage between spawner abundance and ecosystem response (e.g., response of macroinvertebrate communities to changes in escapement). Candidate indicators relate to the specific data that could be collected or models that might be used to represent the indicator themes. This list represents the full range of candidate indicator themes that we believe are worth exploring, not necessarily the core list of indicators that should be integrated as part of Strategy 3. Future efforts will be required to narrow this list to a more manageable number.

Table E1. Summary of the suggested indicator themes and candidate indicators.

Type I Indicators—Which factors affect spawner abundance?

Indicator theme	Candidate indicators
marine conditions	sea surface temperature (SST) Pacific Decadal Oscillation (PDO) El Nino-Southern Oscillation (ENSO) Coastal Upwelling Indices Oyster Condition Indicator
harvest rate	catch accounting
implementation uncertainty	difference between management target and realized target
stock abundance	abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) escapement estimates (NuSEDs)
enroute mortality	discharge estimates of enroute mortality water temperature disease incidence / virulence
abundance of predators	abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter, sea lions, harbour seals

Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values?

Indicator theme	Candidate indicators
human disturbance (forestry, agriculture, effluent sources)	area of agricultural activity watershed area with forest harvesting location of point source discharges
restoration activities	lake fertilization stream fertilization carcass enhancement forest fertilization
watershed / ecosystem characteristics	elevation BEC stream geomorphology groundwater EAU BC
hydrology	discharge lake flushing rate annual precipitation watershed drainage area
vegetation cover	BEC length of stream with riparian harvesting riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)
bedrock geology	classification of bedrock geology
microbial processing	uncertain

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bedrock geology	classification of bedrock geology
microbial processing	uncertain

water quality / chemistry	N concentration (nitrate, nitrite, ammonia) P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) acidity (pH), alkalinity water temperature Total dissolved solids (TDS)
spawner abundance	escapement estimates historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)
salmon distribution	fish distribution mapping
distribution of predators	distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter
abundance of predators	abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter

Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems?

Indicator theme	Candidate indicators
water quality / chemistry	N concentration (nitrate, nitrite, ammonia) P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)
primary productivity	algal (blue-green algae), macrophyte, and/or phytoplankton biomass chlorophyll a diatom biomass (or community diversity)
secondary productivity	zooplankton biomass (or community diversity)
macroinvertebrate production	index of biological integrity (IBI) invertebrate biomass (or community diversity)
juvenile fish production	salmon smolt abundance juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) juvenile weight
timing of stock migration	migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)
sediment layer	analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)
fine sediment layer	uncertain
vegetation	foliar N and ^{15}N of selected species tree growth
wildlife	^{15}N of bear fur density and abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter
riparian insects	^{15}N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)

Section V—Recommended Next Steps

To build on this work and help those engaged in implementing Strategy 3 of the Wild Salmon Policy we offer the following recommendations:

1. *Specify ecosystem objective and benchmarks*: Setting objectives addresses the need to specify the "ecosystem values" of interest to the public and decision makers. Benchmarks provide the comparison against which indicator trends can be properly assessed, i.e., are things improving, deteriorating or staying the same?

2. *Establish a basis for identifying variation in ecosystem response*: The effects of salmon on freshwater ecosystems vary considerably and depend on factors, such as the magnitude, timing, and distribution of spawning runs, carcass retention capacity, nutrient storage capacity, water temperature and discharge, background inputs of nutrients and allochthonous organic matter, as well as the composition of the biological community. Scientists and managers will therefore need to consider how ecological responses vary with the conditions of individual catchments. Spatial stratification of watersheds in B.C. would help scientists understand ecosystem response to marine-derived nutrient inputs.

3. *Conduct extensive comparisons across multiple watersheds:* Existing biological and physical provincial datasets should be explored opportunistically to clarify the linkages between physical processes at different scales and varied biological responses relating to nutrient enrichment. Recent unpublished research suggests that exploring such landscape level classifications may have considerable management utility.

4. *Conduct large-scale field experiments*: Most evidence regarding effects of marine-derived nutrients on ecosystem indicators is represented by observational studies demonstrating statistical correlations. Hence, there are cautions when interpreting these results; large-scale experimental manipulations of lakes, streams, or watersheds would be much more useful in establishing causal mechanisms. Field experiments need to (1) determine a reasonable set of core watershed and habitat covariates that can be used for matching treatment-control pairs and (2) provide significant contrasts between treatment and control replicates. Other experimental design principles also need to be considered.

5. *Conduct comprehensive status and trend monitoring*: Once a list of core indicators have been selected, broad monitoring of these indicators in the field should be based on a probabilistic sampling design that allows valid inferences across broad spatial scales.

6. *Use an adaptive management approach*: Implementation of Strategy 3 of the WSP requires a management system with an explicit recognition of key uncertainties (i.e., admitting what we don't know) and a commitment to learning (i.e., reducing the uncertainties).

List of Acronyms

BEC	Biogeoclimatic Ecosystem Classification	**NCC**	Nature Conservancy of Canada
CUI	Coastal Upwelling Index	**NMFS**	National Marine Fisheries Service
DFO	Department of Fisheries and Oceans	**NRC**	National Research Council
EAU	BC Ecological Aquatic Units for BC	**NuSEDs**	Salmon Escapement Database System
EMAP	Environmental Monitoring Assessment Program	**OCI**	Oyster Condition Indicator
ENSO	El Nino-Southern Oscillation	**PDO**	Pacific Decadal Oscillation
EPA	United States Environmental Protection Agency	**PNAMP**	Pacific Northwest Aquatic Monitoring Partnership
GRTS	Generalized Random Tessellation Stratified	**SRP**	Soluble reactive phosphate
IBI	Index of biological integrity	**SST**	Sea surface temperature
ISAB	Independent Scientific Advisory Board	**TDS**	Total dissolved solids
MD	Marine-derived	**TP**	Total phosphorous
MOE	BC Ministry of the Environment	**WSP**	Wild Salmon Policy

I. CONTEXT

Canada's Wild Salmon Policy (WSP) was released in June 2005 with a goal to restore and maintain healthy and diverse salmon populations and their habitats (DFO 2005). To help decision makers measure progress towards their goals, indicators are being developed as part of two WSP Strategies. Strategy 2, Action Step 2.2, proposes development of "*habitat indicators*" to measure the suitability of freshwater habitats, such as water quality, physical habitats, or food availability, for Pacific salmon (*Oncorynchus* species). This Action Step is generally helping to answer:

> *How does freshwater habitat quality affect Pacific salmon?*

Strategy 3, Action Step 3.1 is the focus of the work described here, which aims to include ecosystem values and monitoring in decision-making by proposing indicators to monitor the status of freshwater and terrestrial ecosystems. In contrast to Action Step 2.2, these "*ecosystem indicators*" are generally concerned with answering:

> *How do Pacific salmon affect freshwater and terrestrial ecosystems?*

The scientific basis for proposing ecosystem indicators within the WSP and for salmon management recognizes that Pacific salmon play an important role in marine, freshwater, and terrestrial ecosystems, including streams, lakes, riparian forests and wildlife food webs. For instance, recent papers have highlighted the importance of salmon in contributing marine-derived nutrients (e.g., phosphorous and nitrogen) which fertilize riparian vegetation, streams, and lakes, thereby enhancing productivity (Cedarholm et al. 2000; Gende et al. 2000; Naiman et al. 2002; Schindler et al. 2003). Spawning salmon and their carcasses can also act as a food source for various species of terrestrial wildlife, such as osprey, eagles, otters, bears and wolves.

In spite of these potential benefits, some concerns have been raised about an "over-escapement" or "over spawning" hypothesis which suggests that high numbers of salmon returning to the spawning grounds can reduce the number of salmon produced, ultimately leading to stock collapse in the following generation(s). Recent evidence, however, does not support hypothesis of stock collapse (Walters et al. 2004), though recruitment per spawner generally declines with higher escapement due to density dependent effects. For example, reduced spawner efficiency (i.e., recruits per spawner) could result from crowding on the spawning grounds, leading to an increase in egg mortality due to increased redd disturbance, egg superimposition, or depletion of oxygen supplies in the gravel. Regardless, having too many salmon is seldom a problem. Salmon in some areas have been eliminated from 40% of their historic range (NRC 1996 as cited in Gresh et al. 2000), and contributions of biomass and nutrients from salmon to their spawning grounds are at 7% of historic levels (Gresh et al. 2000).

Put simply, managers influence freshwater and terrestrial ecosystems by their choices in managing spawner abundance. Changes in fisheries regulations (i.e., harvest levels) and artificial enhancement (e.g., hatcheries), will affect other ecosystem components. The role of ecosystem indicators is to provide a measure of ecosystem responses to changes in spawner abundance, thereby helping managers understand how changes in their actions affect freshwater and terrestrial ecosystems.

Deciding upon appropriate changes in fishery management actions is not an easy task due to a variety of management and scientific challenges. First, decisions about changes in harvest rates and hatchery practices are often controversial. Catch is allocated amongst a variety of competing objectives: conservation; First Nations food, social and ceremonial fisheries; commercial fisheries; and recreational harvesting. There could also be challenges to using hatcheries to increase populations. Evidence suggests that interbreeding of hatchery fish with wild fish reduces the population health (or fitness) of wild stocks (ISAB 2002), which may be in direct conflict with the Wild Salmon Policy. As well, artificial enhancement of salmon populations might encourage harvest rates that are unsustainable for wild populations and thus mask downward trends (Gardner et al. 2004). Second, it is difficult to manage spawner abundance for five salmon species with multiple human and ecosystem objectives. These species are harvested at different geographic locations with varying levels of effort, migrate and intersect fisheries at different times of the year, and are valued differently by First Nations, commercial, and recreational harvesters. Third, given the number of scientific uncertainties about the role of salmon in freshwater and terrestrial ecosystems, it is difficult to select the best ecosystem indicators and set targets that are scientifically defensible. We do not fully understand the role and relative importance of salmon in sustaining sensitive wildlife populations, which would be useful information when setting escapement targets. As stated in the Wild Salmon Policy (DFO 2005), "few studies provide advice on the numbers of salmon necessary for healthy freshwater ecosystems", though some studies promote using ecological objectives to set management targets (e.g., Peery et al. 2003), while others have started tackling this problem (e.g., Schmidt et al. 1998; Bilby et al. 2001).

This report serves three functions: (1) provide a first attempt at developing ecosystem indicators for Strategy 3 of the Wild Salmon Policy; (2) recommend further development and further refinement of ecosystem indicators; and (3) suggest next steps. We hope to reduce confusion about the interpretation and implementation of Strategy 3 of the WSP (see Norton-Arnold & Company 2005a; 2005b). We do not however attempt to provide a comprehensive written summary of the scientific research conducted to-date on the role of salmon in terrestrial and freshwater ecosystems. Several good summary papers already provide that information (e.g., Cedarholm et al. 2000; Gende et al. 2000; Naiman et al. 2002; Schindler et al. 2003). Rather, we reviewed the literature to develop a *better understanding of the linkages* among the five Pacific salmon species and freshwater / terrestrial ecosystems, and used our resulting summary on the "state of the science" to provide a scientific rationale for *recommending ecosystem indicators* and *next steps*.

Recognizing that we couldn't address all potentially relevant issues within the scope of this project, we constrained our work in three ways. First, we focused on understanding the role of salmon *spawners*, *carcasses*, and to a lesser extent *eggs*, in contributing to changes in the broader freshwater and terrestrial ecosystems (Figure 1). We did not look at the broader ecosystem effects of other life stages, even though these stages may have important influences. Second, we did not specify the way in which each of the five salmon species may interact differently with their surrounding ecosystems, which might affect the choice of indicators. Third, we focused on the role of salmon in contributing to nutrient and food budgets in freshwater (streams and lakes) and terrestrial (riparian vegetation and wildlife) ecosystems (Figure 1, links 3 and 4). We did not examine the role of salmon in other freshwater ecosystem processes (e.g., bioturbation of stream environments; Figure 1, link 5), in marine environments (e.g., salmon as a food source for seals and sea lions, NMFS 1997), or in human societies (e.g., cultural and economic significance).

The remainder of this report is organized into four sections:

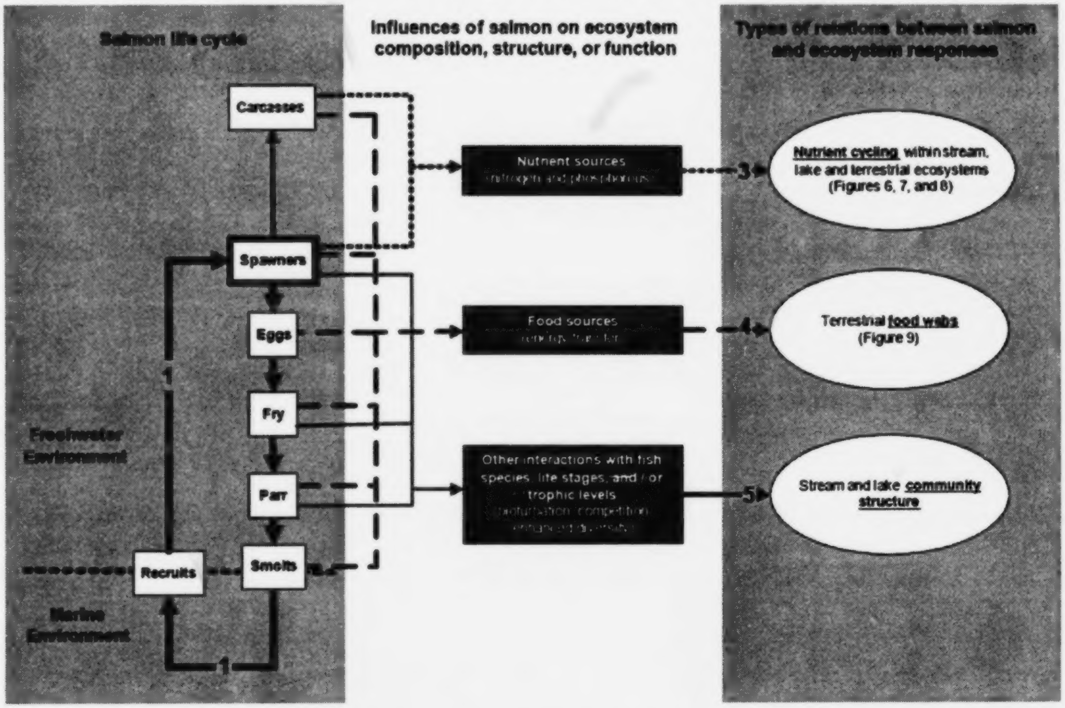
- Section II provides a conceptual framework for thinking about the problem of incorporating ecosystem considerations into salmon management decisions;
- Section III describes our systematic approach to identifying indicators;
- Section IV summarizes our review of the literature, as well as the recommended indicator themes and indicators; and
- Section V lists a series of recommendations for next steps to identify and develop a core list of ecosystem indicators for the Wild Salmon Policy.

II. MANAGEMENT PROBLEM

Policy makers and managers are moving from single species management to a multi-species, ecosystem approach. The five species of Pacific salmon act as "*keystone species*," affecting freshwater and terrestrial ecosystem composition, structure, and function (e.g., Willson and Halupka 1995). A key scientific challenge is understanding the relative importance and influence of salmon on these three elements, across different locations and times.

Figure 1. Illustration of the relationships between the life stages of Pacific salmon and influences on ecosystem composition, structure, or function.

Each life stage of salmon may have an influence on the freshwater ecosystem (represented by the links between the life stages on the left and boxes in the centre). Salmon influences on ecosystems have been grouped into three categories: nutrient sources, food sources, and interactions with other life stages, fish species, or trophic levels. The focus of this work was to review the role of salmon spawners, carcasses, and to a lesser extent eggs, on nutrient cycling (pathway 3) and terrestrial food webs (pathway 4). The role of salmon as a food source in aquatic ecosystems is considered herein as part of nutrient cycling (pathway 3). Numbered linkages are described further in Appendix A.


Salmon life cycle
Influences of salmon on ecosystem composition, structure, or function
Types of relations between salmon and ecosystem responses
Carcasses
Spawners
Eggs
Fry
Parr
Smolts
Recruits
1
1
Freshwater Environment
Marine Environment
Nutrient sources
(nitrogen and phosphorous)
Food sources
(energy transfer)
Other interactions with fish species, life stages, and / or trophic levels
(bioturbation, competition, enhanced diversity)
3
4
5
Nutrient cycling within stream, lake and terrestrial ecosystems (Figures 6, 7, and 8)
Terrestrial food webs (Figure 9)
Stream and lake community structure

Salmon may affect *ecosystem composition*—the other biological, chemical or physical features of stream, lake, and riparian ecosystems (e.g., presence/absence of a species or species composition, water chemistry, streambed composition). For instance, numerous isotope studies demonstrate that marine-derived nutrients from salmon can be found in riparian vegetation (Reimchen 2001, Helfield and Naiman 2002, Reimchen et al. 2002, Mathewson et al. 2003, Bilby et al. 2003, Wilkinson et al. 2005, Koyama et al. 2005, Bartz and Naiman 2005), and wildlife species (Ben-David et al. 1998, Hilderbrand et al. 1999, Reimchen 2001, Darimont and Reimchen 2002). Various authors have inferred ecological effects of salmon nutrient subsidies such as increased carrying capacity of bear populations (Schindler at al. 2003), increased size of individual bears (Hilderbrand et al. 1999), and changes in the timing of lactation in mink (Ben-David and Schell

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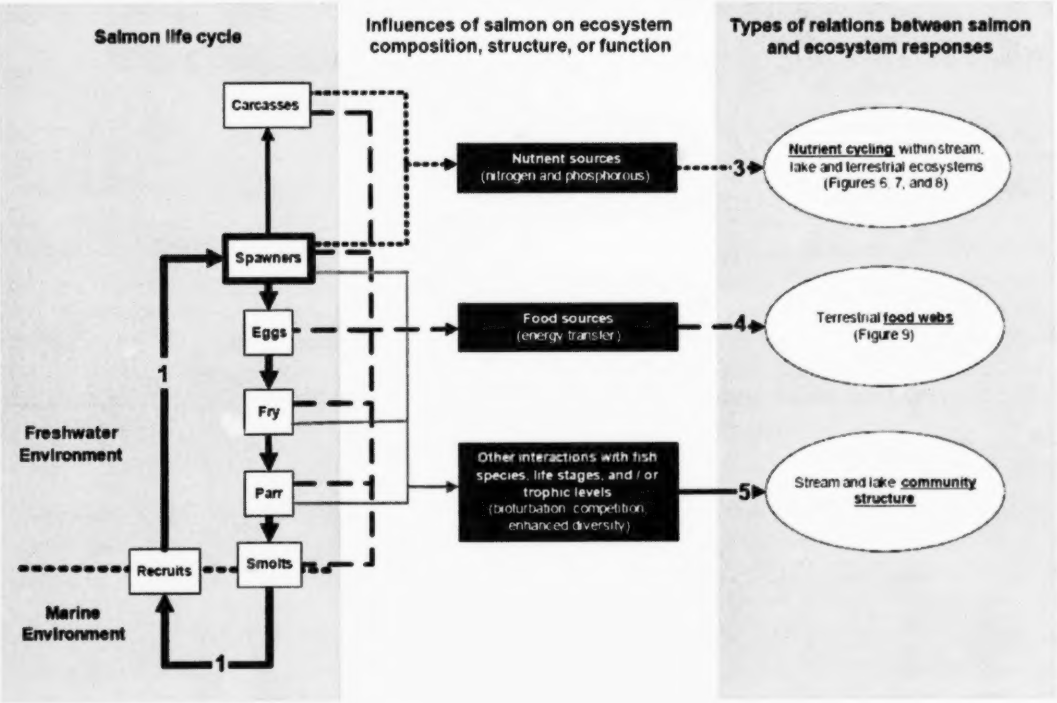

Salmon life cycle
Influences of salmon on ecosystem composition, structure, or function
Types of relations between salmon and ecosystem responses
Carcasses
Spawners
Eggs
Fry
Parr
Smolts
Recruits
1
1
Freshwater Environment
Marine Environment
Nutrient sources
(nitrogen and phosphorous)
Food sources
(energy transfer)
Other interactions with fish species, life stages, and / or trophic levels
(bioturbation, competition, enhanced diversity)
3
4
5
Nutrient cycling within stream, lake and terrestrial ecosystems
(Figures 6, 7, and 8)
Terrestrial food webs
(Figure 9)
Stream and lake community structure

Salmon may affect *ecosystem composition*—the other biological, chemical or physical features of stream, lake, and riparian ecosystems (e.g., presence/absence of a species or species composition, water chemistry, streambed composition). For instance, numerous isotope studies demonstrate that marine-derived nutrients from salmon can be found in riparian vegetation (Reimchen 2001, Helfield and Naiman 2002, Reimchen et al. 2002, Mathewson et al. 2003, Bilby et al. 2003, Wilkinson et al. 2005, Koyama et al. 2005, Bartz and Naiman 2005), and wildlife species (Ben-David et al. 1998, Hilderbrand et al. 1999, Reimchen 2001, Darimont and Reimchen 2002). Various authors have inferred ecological effects of salmon nutrient subsidies such as increased carrying capacity of bear populations (Schindler at al. 2003), increased size of individual bears (Hilderbrand et al. 1999), and changes in the timing of lactation in mink (Ben-David and Schell

1997, cited in Naiman et al. 2002). However, there is little information to quantify the relationships between numbers of spawners and these effects in terrestrial species.

Salmon may affect *ecosystem structure*—a description of the arrangement of ecosystem components. Consider a hypothetical example in which a field biologist samples two lakes, both with the same resident fish species and thus the same *composition*. A key difference though is that the lakes have different proportions of the populations at various ages and sizes, due to size-selective fishing pressure in one lake. This difference could affect population dynamics and species interactions within each lake. For an example more relevant to Pacific salmon, some have suggested that increases in spawner abundance increase rates of straying of salmon from their natal streams, thereby enhancing biodiversity via changes in the genetic structure of other salmon stocks (Walters et al. 2004).

Salmon may also affect *ecosystem function*—the natural ecosystem processes of creation and destruction. For instance, salmon can act as ecosystem engineers when digging redds (Schindler et al. 2003). Such physical alterations of a streambed can change water-flow patterns (Burner 1951 as cited in Schindler et al. 2003), promote channel migration, alter sediment accumulation (Kondolf et al. 1993 as cited in Schindler et al. 2003), and decrease algal biomass and macroinvertebrate densities (Moore et al. 2004). This role of salmon in an ecosystem is very different than one where salmon's influence relates to changes in ecosystem composition or structure.

We used conceptual diagrams (e.g., Figures 1) and information tables (Appendix A) to summarize our review of the literature and structure our thinking about how ecosystem indicators could be used to evaluate the effect of changes in fish management actions (e.g., Jones et al. 1996). Figure 1 provides a general overview of what is known about the potential influences of salmon on streams, lakes, and riparian communities. The left side of this diagram distinguishes the various stages and progression of the salmon life cycle through freshwater and marine environments. The "spawners" box (white box with thick black outline) denotes the life stage over which managers can have the greatest influence, by such actions as adjusting harvest rates, hatcheries operations, or habitat conditions. Although salmon spend much of their life in the ocean, the influence of salmon on marine ecosystems is not as well known as in freshwater, and was excluded from our investigation.

Linkages (arrows) between the life stages on the left side of Figure 1 and three categories of influence in the center of the figure represent known relationships that have been documented in the literature or hypothesized relationships that are believed to be important. Carcasses and spawners, and to a lesser extent eggs, are the only sources of nutrient subsidies from marine to freshwater environments (dotted lines). Linkage #3—the effects of salmon on nutrient cycling—represents the bulk of the research and the emphasis of our review. This pathway also implicitly includes the value of salmon as food in freshwater ecosystems. All freshwater stages can provide a source of food and energy transfer between salmon and other fish or wildlife species (dashed lines). Linkage #4—the role of salmon in terrestrial food webs—is also well studied, though we have focused only on the role of carcasses and spawners in this capacity. Spawners, fry, and parr can have other important interactions with the broader ecosystem, that aren't represented by the first groupings (grey lines). For instance, while digging redds, spawners can alter physical stream environments or affect egg survival in crowded spawning areas. While returning to natal streams large numbers of adults may slow migration at certain flows and spatial pinch points leading to increases in enroute mortality. While rearing in lakes, changes in the number of salmon fry and parr may increase the level of competition for limited food resources with resident fish species.

Linkage #5—interaction of salmon with other fish species, life stages, and/or trophic levels—is not discussed thoroughly in this report. We did not consider these relationships for indicator development because our level of scientific understanding is lower than for the other relationships, due to complex interactions. There are many covariates and potentially confounding factors in linkage #5, which make it difficult to clarify the effects of salmon. For example, to reliably understand the relative importance of salmon in altering streambeds, we also need to understand the role of hydrology, watershed topography, and upslope forestry disturbances as these factors may also contribute to channel formation.

Ecosystem indicators developed as part of Strategy 3 are intended to bridge the gap between science and decision-making. Conceptually the role of science-based indicators in this capacity can be illustrated using Figure 2, where the x-axis represents spawner abundance and the y-axis represents a measurable value for an ecosystem indicator of interest. The relationship between these two variables is represented by the non-linear curve (thick black line) which is hypothetical, though realistic for some ecosystem indicators. For example, biofilm and benthic macroinvertebrate standing stocks are known to reach an asymptote at intermediate levels of carcass abundance (Wipfli et al. 1998; 1999—from Gende et al. 2002).

Using the hypothetical relationship in Figure 2, we can see how managers could affect freshwater ecosystems by their actions. Changes in harvest rates that affect spawner abundance—point along the x-axis in Figure 2—correspond to some related change in some measurable attribute of the ecosystem—point along the y-axis. Thus, when setting management targets (grey vertical line) with ecosystem objectives (reflecting ecosystems values) in mind, managers should consider the anticipated ecological response of those targets (corresponding value along the y-axis). However, there are a variety of considerations when setting management targets for escapement, each of which has implications on the location of a management target along the x-axis. *Optimum harvest*, or the maximum sustained yield, is one objective which managers consider when determining the total catch across First Nations, commercial, and recreational harvesters. This objective will most likely yield a different escapement target from a focus on the objective of ensuring the *long-term sustainability* of each salmon species. An escapement target based on *conservation objectives* would include escapement needs for long-term viability, plus a safety factor and potentially a stock rebuilding factor. An *ecosystem target* would provide some measurable benefits for the broader ecosystem, which could again differ from the above targets, but might be rolled into a conservation target.

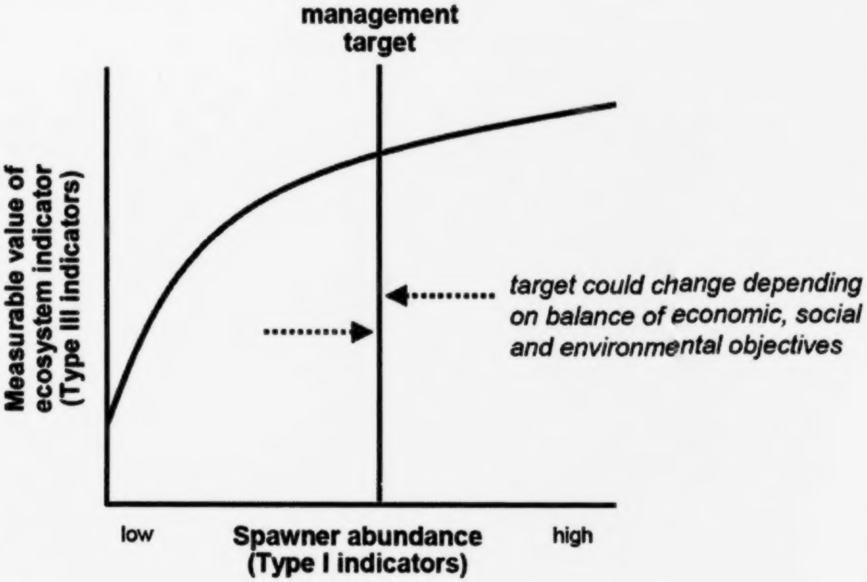
The framework in Figure 2 can be used for several purposes in Strategy 3 of the WSP:

1. Clearly identifying the ecosystem values, objectives and indicators (see Recommendation 1 in Section V for more information on this)—i.e., what are the variables of interest on the y-axis? The figure may provide a useful tool for clarifying the overarching ecosystem objectives by prompting participants in the process to consider possible responses of specific variables.
2. Deciding upon a suitable range of responses within which to maintain an ecosystem indicator—i.e., what is a suitable range of values along the y-axis within which to manage an ecosystem? Delineating preferred "zones" of response along the y-axis, rather than single numeric targets, may be helpful because they are better at accommodating uncertainties—particularly natural variation in ecosystem responses along the y-axis. Such approaches, termed traffic lights or limit reference points, are useful ways to think about benchmarks which are being applied in different contexts elsewhere in fisheries management (Caddy 2002). These benchmarks can then be used to track the progress of management efforts over time.

3. Determining sufficient levels of escapement to maintain ecosystem responses of interest within the preferred "zones" of response—i.e., what are some target levels of escapement which will meet ecosystem objectives? These discussions need to occur within the context of other decisions (e.g., setting harvest rates) as there are obvious implications. Such targets should account for the management uncertainty in actually implementing an intended escapement target.

Figure 2. Hypothetical relationship (thick black line) between spawner abundance and an ecosystem indicator of interest.

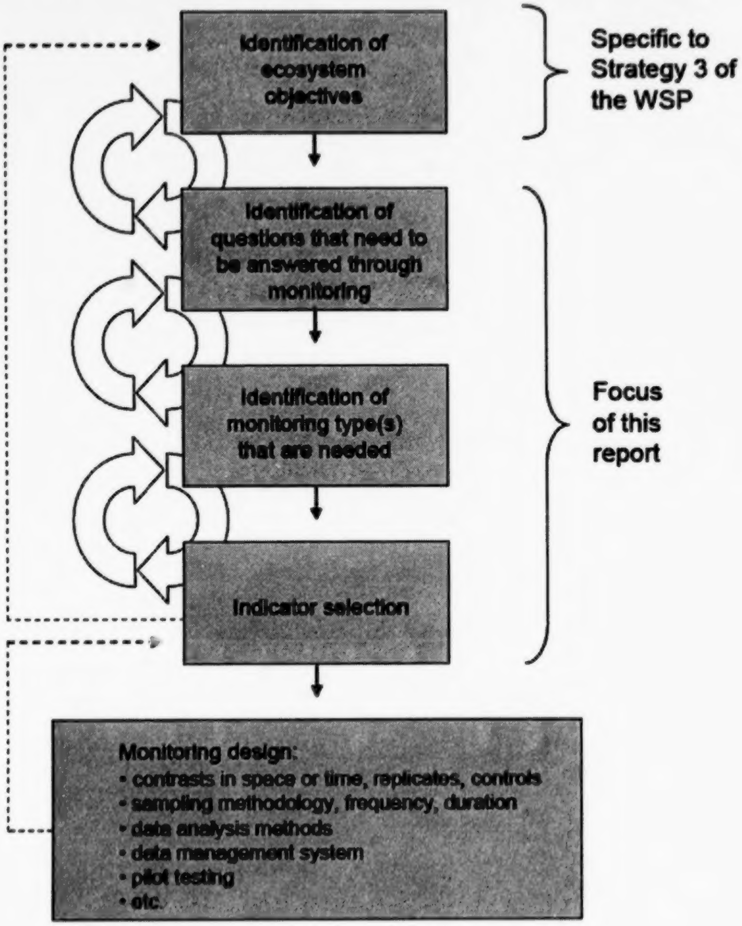
The vertical grey line indicates a point along the x axis at which a manager may set some target escapement based on achieving one of a variety of goals (e.g., optimum harvest or conservation).



III. APPROACH TO IDENTIFYING INDICATORS

In this Chapter we describe how we have identified potential indicators for Action Step 3.1 in the Wild Salmon Policy (WSP). The steps follow the generic sequence shown in Figure 3, a simplified illustration of an adaptive management framework, described in Section V.

Figure 3. Simplified monitoring development process for Strategy 3 of the WSP.


Identification of ecosystem objectives
Specific to Strategy 3 of the WSP
Identification of questions that need to be answered through monitoring
Identification of monitoring type(s) that are needed
Focus of this report
Indicator selection
Monitoring design:
• contrasts in space or time, replicates, controls
• sampling methodology, frequency, duration
• data analysis methods
• data management system
• pilot testing
• etc.

Relevance to Management

Articulating management challenges in the form of questions that affect decisions can be a very effective approach for prioritizing information and monitoring needs, as well as guiding monitoring design and indicator selection (e.g., EPA's Data Quality Objectives process; EPA 2000). Monitoring programs that are not well thought through will not provide information that is most relevant to managers. We have identified three questions that relate to monitoring and indicator needs under Strategy 3 of the Wild Salmon Policy, and the indicators we suggest in this report (listed in Section IV and Appendix C) have been grouped into three categories that relate to each of these questions.

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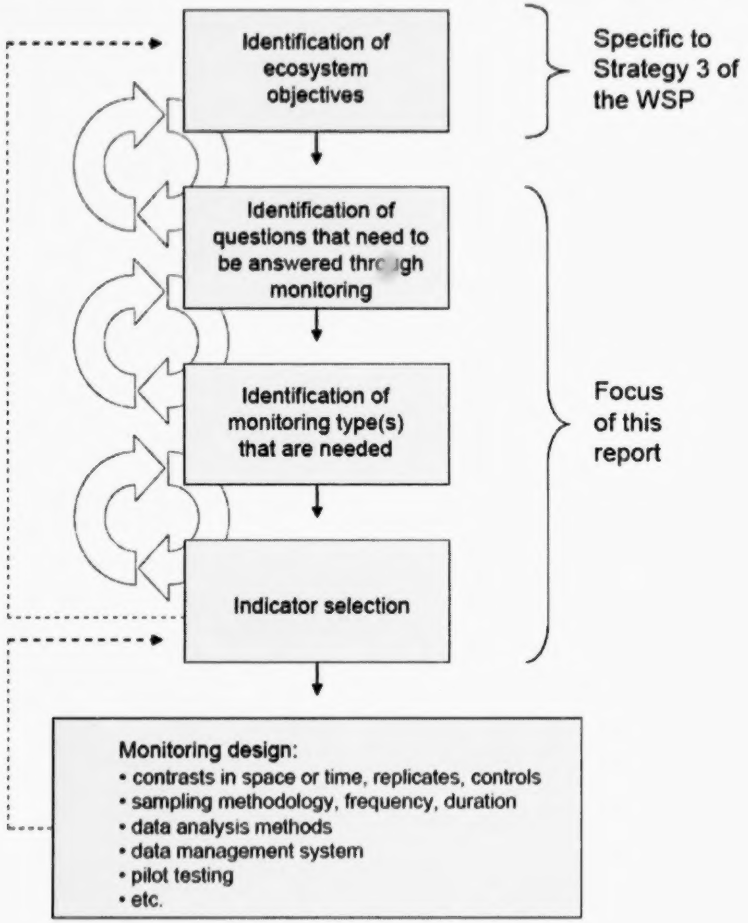
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Type I indicators are intended to help answer the question, *"Which factors affect spawner abundance?"* This question is important for understanding how successful managers' actions are in achieving ecosystem objectives. Both human factors (changes in harvest) and natural factors (changes in marine conditions and enroute mortality) affect the number of spawners returning to natal streams—i.e., location along the x-axis in Figure 2. Managers need to know that their actions are actually having their intended effects both on achieved escapement levels and on the ecosystem, rather than outcomes being the result of some confounding factor which is naturally driving changes in escapement. Factors that control natural changes in abundance are obviously important and consequently integrated in pre-season and in-season salmon forecasting models. Thus, Type I indicators are intended to help managers understand the effect of **all** factors on spawner abundance, both within and outside of their control.

Type II indicators are intended to answer the question, "*In which areas will increases in spawner abundance have the greatest influence on other ecosystem values?"* As indicated by Figure 1, salmon contribute important marine subsidies of food and nutrients to freshwater environments. Although important in some watersheds, not all watersheds are equally reliant on these subsidies (i.e., some are not nutrient limited). The implication of this observation to managers is illustrated in Figure 4. Relationship A represents a hypothetical non-linear form of an ecosystem response in a watershed that is nutrient limited (e.g., an oligotrophic, coastal watershed that is rapidly flushed by high runoff), while relationship B represents a linear response in a watershed that is not resource limited (e.g., a watershed in BC's Interior with nutrient rich soils and low precipitation). In both cases, the value for an ecosystem indicator is greater than zero, but the shape of the response to changes in spawner abundance is very different. Given these two cases, a manager would be most interested in adjusting spawner abundance in watershed A because they would anticipate a positive response to their actions, relative to watershed B where they would expect no obvious benefits. We expect that managers will want to identify high priority areas that are nutrient or food limited, such that increasing numbers of spawners will most likely have the greatest positive effect on freshwater, riparian, or terrestrial ecosystems. These areas will obviously include watersheds that are either currently or historically known to have supported salmon. This will help salmon managers both maintain ecosystem conditions in areas where salmon provide important contributions today, and attempt to restore conditions in locations where salmon were historically more abundant.

Type III indicators will ultimately help managers understand the response of an ecosystem indicator to their actions by asking, "*How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems?"*. Ecosystem responses may take a variety of shapes (see Figure 5, relationships A, B, C, and D) and it is not clear how any one indicator will respond in a particular watershed. Such variations in the shape of responses have implications on how managers set escapement targets. For instance, consider the dashed vertical lines in Figure 5, which represents a management target set at a spawner abundance with only maximum sustained yield or salmon conservation goals in mind. The solid vertical lines represents a higher target corresponding to a new goal that also considers ecosystem values. Although ecosystem objectives were not explicitly considered in the original management targets, it likely provides some benefits to ecosystem values—i.e., an increase in an indicator to the left of the target. Thus, when adding ecosystem considerations into decision making, managers should focus on trying to set targets that provide the greatest benefit to those relationships or indicators that are expected to show the greatest positive incremental changes above the original targets (Figures 5 A and C). Thus, managers will need to consider tradeoffs among the various indicators as the direction and magnitude of change (positive or negative) in indicator response between the "old" and "new" management targets across the full suite of indicators may vary, and the challenge will be to find an optimal new target that balances these tradeoffs (explained further in Figure 5).

Figure 4. Two hypothetical relationships between spawner abundance and an ecosystem indicator.

Relationship A (solid curve) represents the response of an indicator in a watershed that is nutrient limited, and where increases in spawner abundance will lead to positive changes in the ecosystem indicator. Relationship B (dashed line) represents the response of the same indicator in a watershed that is not nutrient limited, and where increases in spawner abundance have no effect on the response of the ecosystem indicator.

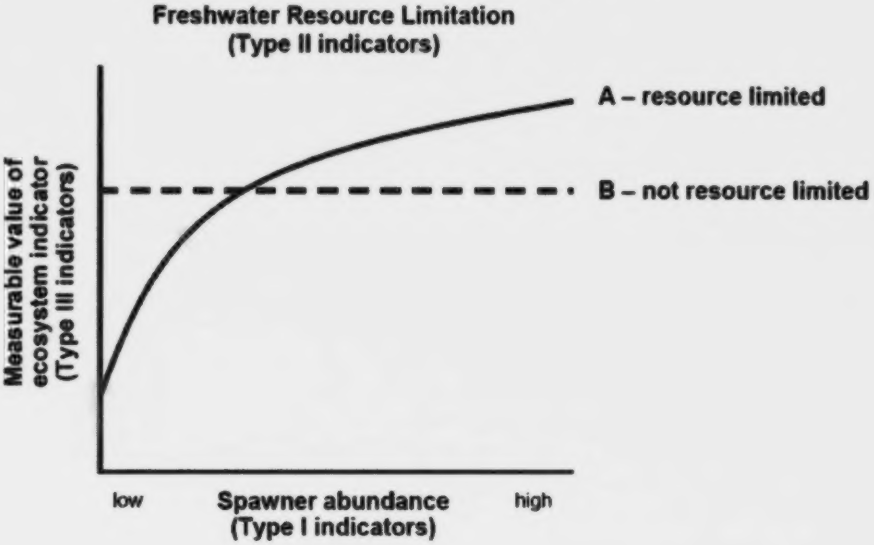
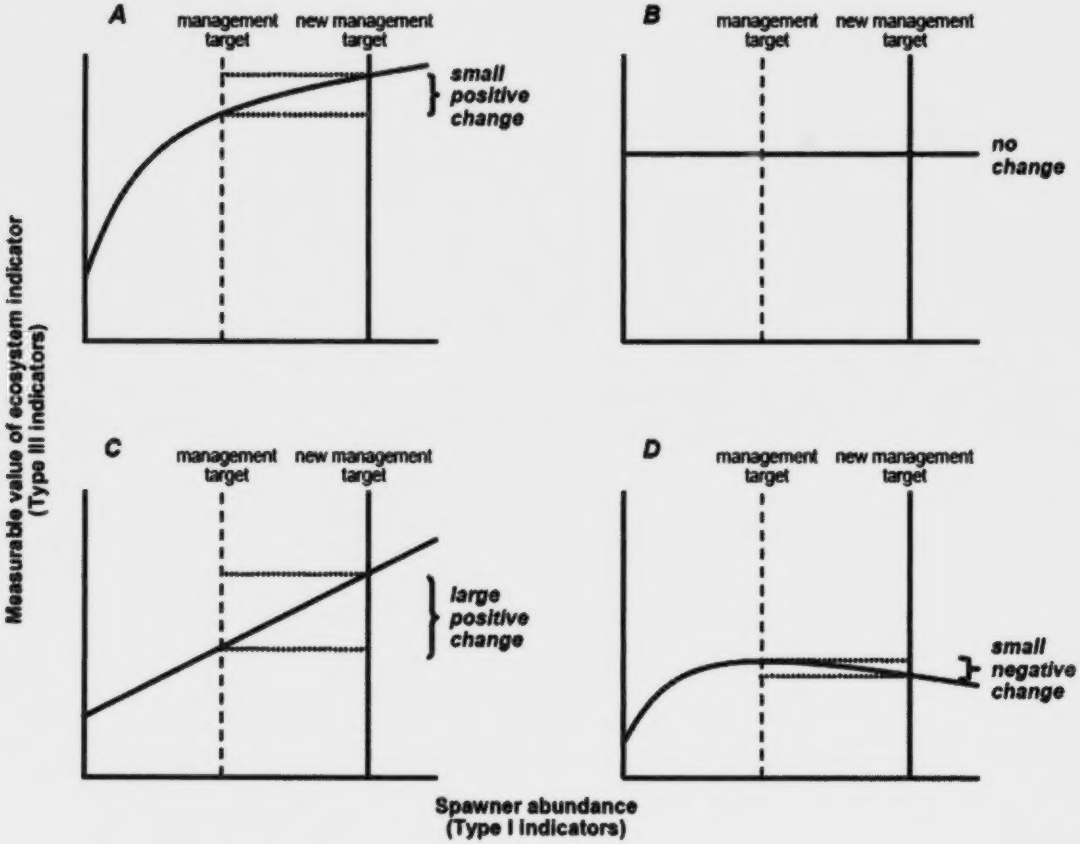


Figure 5. Four hypothetical relationships (four thick black lines, A-D) between spawner abundance and ecosystem indicators.

The vertical lines represent the spawner abundance at which a management target could be set when failing to consider (dashed lines) or considering (solid lines) ecosystem values in decision making. When developing new management targets managers should try to optimize benefits for those indicators that are likely to show the greatest positive incremental change above original targets, indicated here by the differences between the dotted horizontal lines, while being aware of any tradeoffs that might be required.For example, how far to the right on the x axis can the new target be set before the negative effect on indicator D (as well negative effects on social and economic indicators related to lower harvest levels) outweighs the positive effects on indicators A and C? Ecosystem objectives need to be considered together with other objectives (e.g., harvests for various users).



Types of Monitoring

Different types of monitoring suit different purposes, and several types of monitoring are needed to answer the three management questions discussed above. Our presentation of the indicators in Section IV relates to these type(s) of monitoring:

- *Baseline monitoring*: Characterizing existing environmental conditions, including the natural variability of the factor of interest.
- *Implementation monitoring*: Measuring human activities (what took place, where and when). Implementation monitoring is sometimes very similar to compliance monitoring (what is measured for monitoring compliance with prescribed practices). For example, what a government agency might measure to determine compliance with a management plan may be the same as what is measured by the proponent to document their implementation of the plan.
- *Effectiveness monitoring*: Measuring environmental outcomes of a program, plan, practice, etc. against desired outcomes (specific goals or objectives).
- *Validation monitoring*: Evaluating (1) the degree to which indicators and monitoring techniques measure real environmental outcomes and trends; and (2) the cause-effect relationship between management actions and environmental outcomes. Validation monitoring can be an important component of indicator selection and testing, including the development of appropriate protocols. This typically requires more intensive studies, either to monitor multiple indicators, or to monitor a few indicators very precisely to permit comparisons with less precise approaches (e.g., Tschaplinski and Hyatt 1991, Botkin et al. 2000).

Some of these types of monitoring are interdependent. For example, effectiveness evaluations (determining whether a policy, plan, action, etc. is working) usually require three types of monitoring: baseline, implementation, and effectiveness monitoring. Within an effectiveness evaluation framework, baseline monitoring provides information about the conditions of the ecosystem prior to the action(s) being implemented, to allow for comparisons with conditions afterwards and determine if there has been a response. Moreover, implementation monitoring provides information about what actions were taken (and when), which is necessary for drawing inferences about *why* conditions might have changed. Without implementation data, there is no way to tell if the actions were undertaken as expected or intended; and if the environmental outcomes are not those desired it will be unclear why: were the practices are ineffective, or were the practices not done according to whatever instrument (e.g., policy, guideline, best practice) prescribes them? Finally, effectiveness monitoring focuses on conditions and trends in "outcome" indicators—indicators that represent the management goals and objectives, but must be assessed within the context of baseline conditions and implementation information. Effectiveness monitoring also compels managers to be very specific about desired objectives in terms of on-the-ground outcomes, since it requires that these outcomes to be translated into quantitative indicators that can be measured and assessed.

Indicator Selection

The candidate indicators we suggest are those that we think will best answer the three key questions, based on indicators used or implied in the literature reviewed for this project (see Section IV and Appendix A). We have organized these indicators according to a number of general themes that we believe will facilitate indicator review, as well as the subsequent monitoring design step (the last box in Figure 3).

Table 1 lists the criteria by which we qualitatively evaluated candidate indicators. We looked at three groups of criteria: (1) technical considerations; (2) management relevance; and (3) ecological relevance. We used our review of available data sets to assess the criteria in group 1, our structure for linking management questions to indicators to assess group 2, and our scientific knowledge informed by our literature review (cited in Appendix B) to assess group 3.

Table 1. Indicator evaluation criteria.

Evaluation category	Evaluation criteria
1. Technical considerations	data availability spatial extent temporal frequency additional cost beyond existing programs accuracy and precision
2. Management relevance	related management question (I, II or III described above) relative importance[1]
3. Ecological relevance	strength of cause-effect link[2] indicator of broader ecosystem changes

Few indicators will rate highly across all of these criteria, as each will have strengths and weaknesses. For example, indicators with the greatest management and ecological relevance, and the highest accuracy and precision, may not be readily available and may be too costly to collect. Indicators for which data already exist are the most cost-effective, but may be highly variable across space and time (leading to tests with low statistical power) and were likely collected for a different purpose, resulting in poor alignment with the monitoring questions described above (i.e., have lower ecological or management relevance). Tradeoffs among these criteria are important considerations and difficult to assess. A balance must be found between practicality (what can be realistically achieved in terms of indicator collection and analysis given the available resources) and certainty (the degree to which the indicators directly and comprehensively address the questions at hand). Both intensive and extensive monitoring is of interest.

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[1] Assessment of this criterion requires feedback from interested and relevant parties (managers and the public). This is outside the scope of this project, but it should be included in the next steps.

[2] Our literature review indicated that the strength of cause-effect linkages strongly depends on specific conditions driving ecosystem responses, which vary over space and time.

IV. RECOMMENDED INDICATOR THEMES AND CANDIDATE INDICATORS

We have used "conceptual diagrams" to organize the current state of knowledge regarding the roles that salmon play in freshwater and terrestrial ecosystems. The influences of salmon on nutrient cycling in freshwater and terrestrial ecosystems (arrow 3 in Figure 1), are illustrated in greater detail for salmon-derived nutrient transfer in lakes, streams and riparian/terrestrial systems in Figures 6, 7 and 8, respectively; and the influences of salmon on terrestrial food webs (arrow 4 in Figure 1) are shown in greater detail in Figure 9. These more detailed diagrams follow a consistent approach:

- **Inputs** to each system (the primary input being salmon, from various life stages), and outputs to other systems, are shown as **circles**;
- **Components** within each system that are affected either directly or indirectly by these inputs are shown in **shaded boxes**; and
- The **pathways** or mechanisms by which the inputs are transferred to (directly) or among (indirectly) components are shown as **arrows** (also referred to as "links").

For example, arrow (link) 1 in Figure 9 represents predators such as bears, osprey, bald eagles and otters consuming spawners (catching live fish) or carcasses (feeding on fish that have already spawned and then died), which may effect the population dynamics, density, carrying capacity, growth rate, litter or clutch size, and reproductive success of these species.

Tables 2–5 briefly summarizes each of the linkages in Figures 6, 7, 8, and 9. Readers who wish more in-depth information should refer to Appendix A, which provides evidence for (and, in some cases, evidence against) each of these pathways, as well as information on the management relevance of the pathway, covariates and confounding factors, critical uncertainties, and data requirements for reducing these uncertainties. (The references cited in Appendix A are listed in Appendix B.)

Table 2. Description of the links related to *Nutrient Cycling in Lake Ecosystems* (Figure 6).

Evidence and references are provided in Appendix A. MD = marine-derived.

Link no.	Brief description of link
1	Isotope studies indicate that MD-nitrogen is being transferred to resident fishes. Nutrient transfer results from the direct consumption of dead salmon tissue by fish, or via indirect links between spawners and lower trophic levels, e.g., uptake by primary producers. There is mixed evidence regarding whether increased MD-nutrient inputs translates to higher capacity for nursery lakes to produce sockeye salmon.
2	Relationship between spawners and secondary production in lakes (zooplankton, invertebrates), though evidence is inconsistent. Increased number of spawners may increase secondary production as a result of direct consumption of salmon tissue by invertebrates, or indirectly from increased primary production. However, some studies indicate there may be a negative relationship—increased predation on zooplankton biomass occurs due to a greater abundance of juveniles, which counteracts the potential benefits from MD-nutrient fertilization.
3	Salmon bring MD nutrients into lakes.
4	Nutrients from salmon carcasses can stimulate lake primary productivity via direct chemical uptake.
5	Basic limnology—Secondary producers, such as zooplankton or invertebrates, consume primary producers.
6	Basic limnology—Fish consume zooplankton or invertebrates (secondary producers).
7	Marine-derived nutrients can accumulate in lake sediments via a number of pathways—mediated by incorporation of MD-nutrients into the food web and settling out from water column (i.e., via different trophic levels). Accumulation in sediments can be dominated by settling of plankton, diatoms, or in-situ production of benthic algae.
A	Lake nutrient levels are affected by upstream water supplies and nutrient content of watershed soils.
B	Lake discharge and smolt emigration remove nutrients from lake ecosystems. See 7-D.

Figure 6. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Lake Ecosystems.*

Thin dashed lines 1–3 represent direct links between spawners or carcasses and other ecosystem components (black boxes), while solid lines 4–7 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to / from lake ecosystems. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers could affect ecosystem responses by their actions. See Table 2 and Appendix A for details regarding the nature of these linkages and supporting literature sources.

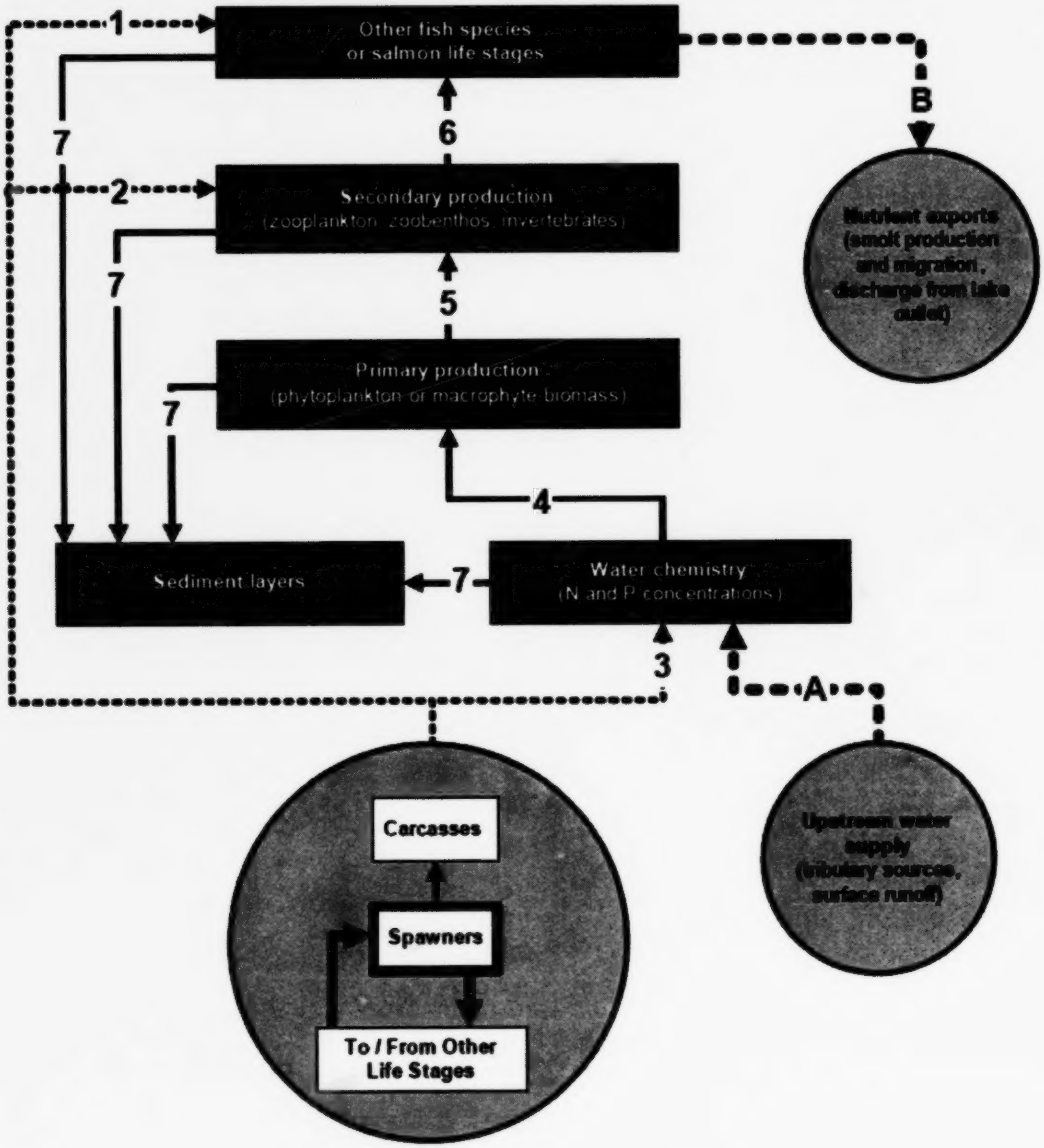

1
Other fish species or salmon life stages
B
7
6
2
Secondary production (zooplankton, zoobenthos, invertebrates)
Nutrient exports (smolt production and migration, discharge from lake outlet)
7
5
Primary production (phytoplankton or macrophyte biomass)
7
4
Sediment layers
7
Water chemistry (N and P concentrations)
3
A
Carcasses
Spawners
To / From Other Life Stages
Upstream water supply (tributary sources, surface runoff)

Figure 6. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Lake Ecosystems.*

Thin dashed lines 1–3 represent direct links between spawners or carcasses and other ecosystem components (black boxes), while solid lines 4–7 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to / from lake ecosystems. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers could affect ecosystem responses by their actions. See Table 2 and Appendix A for details regarding the nature of these linkages and supporting literature sources.

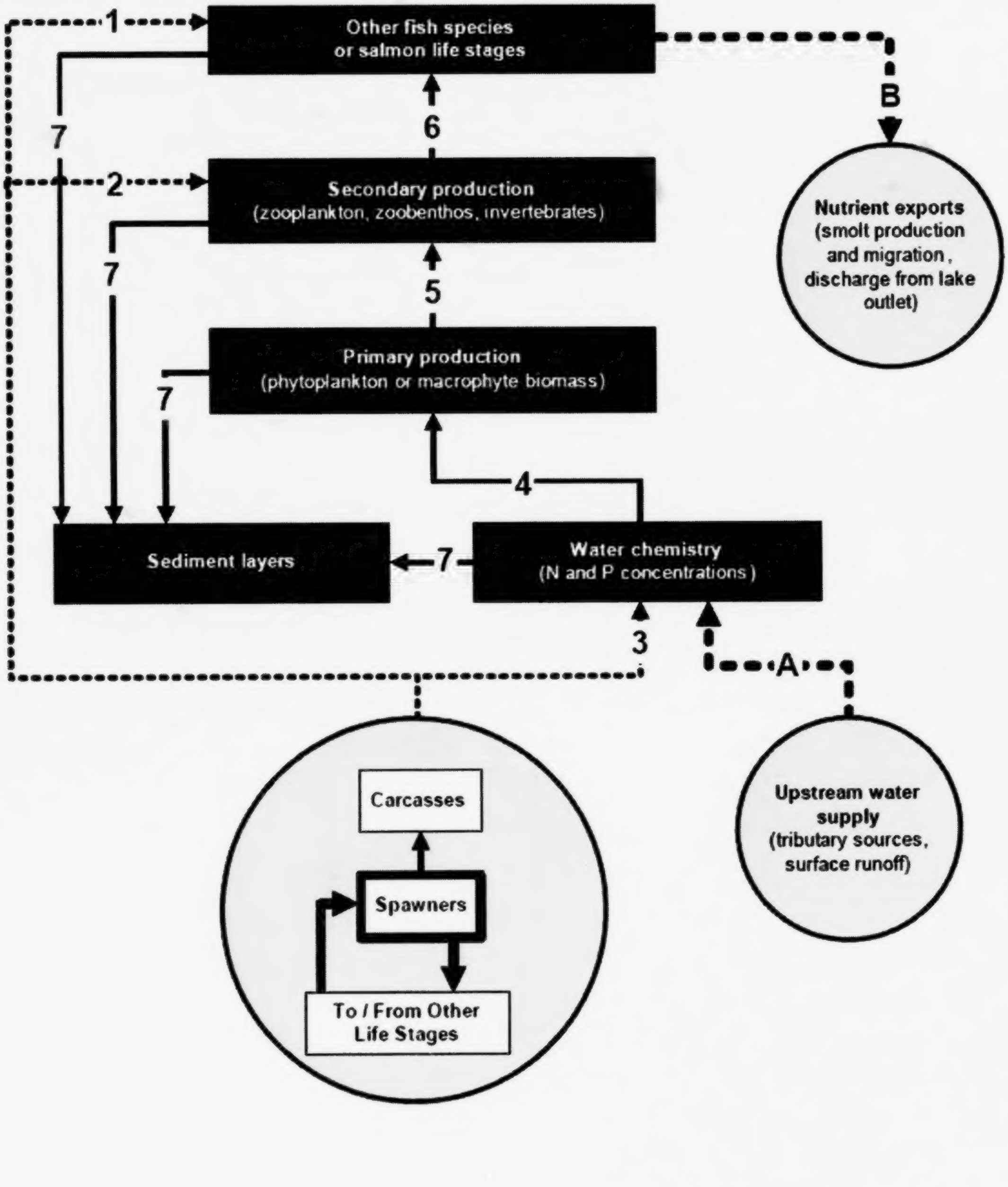

1
Other fish species or salmon life stages
B
7
6
2
Secondary production (zooplankton, zoobenthos, invertebrates)
Nutrient exports (smolt production and migration, discharge from lake outlet)
7
5
Primary production (phytoplankton or macrophyte biomass)
7
4
Sediment layers
7
Water chemistry (N and P concentrations)
3
A
Carcasses
Spawners
To / From Other Life Stages
Upstream water supply (tributary sources, surface runoff)

Table 3. Description of the links related to *Nutrient Cycling in Stream Ecosystems* (Figure 7).
Evidence and references are provided in Appendix A. MD = marine-derived.

Link no.	Brief description of link
1	Juvenile salmon and other fish species may consume flesh from carcasses, or eggs from spawners, resulting in uptake of nutrients into the stream trophic system.
2	Aquatic invertebrates may also consume salmon eggs or flesh from carcasses, resulting in nutrient transfers.
3	Spawning salmon in streams have a direct effect on local water chemistry by altering nutrients concentrations.
4	Nutrients in the water column may be transferred to fine sediment layers in a stream via settling out of the water column or chemical sorption onto the biofilm encrusting streambed and hyporheic surfaces
5	Stream autotrophs (e.g., periphyton, algae, vascular plants) rely on inorganic nutrients in water.
6	Aquatic invertebrates assimilate biofilms (containing marine derived nutrients) that encrust streambed and hyporheic surfaces.
7	Basic limnology—Nutrients may be transferred across trophic levels via consumption of stream primary producers (e.g., phytoplankton) by stream invertebrates.
8	Basic limnology—Marine-derived nutrients affect invertebrate production, which would benefit food availability for other fish species or salmon life stages.
A	Nutrients arrive in streams from the terrestrial environment via litterfall, large woody debris, throughfall, and groundwater sources—to which salmon may have provided some contribution of nutrients.
B	Nutrient imports may arrive from natural, artificial, or salmon sources in upstream environments.
C	Stream nutrient concentration are affected by groundwater sources and exchange.
D	The production of smolts results in the export of nutrients from streams to the ocean, though this portion is relatively small compared to the inputs from adults. Stream discharge will also flush nutrients downstream.

Figure 7. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Stream Ecosystems.*

Thin dashed lines 1–3 represent direct links between spawners, carcasses, or eggs and some other ecosystem components (black boxes), while thin solid lines 4–8 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to/from stream environments. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect stream ecosystems by their actions. See Table 3 and Appendix A for details regarding the nature of these linkages and supporting literature sources.

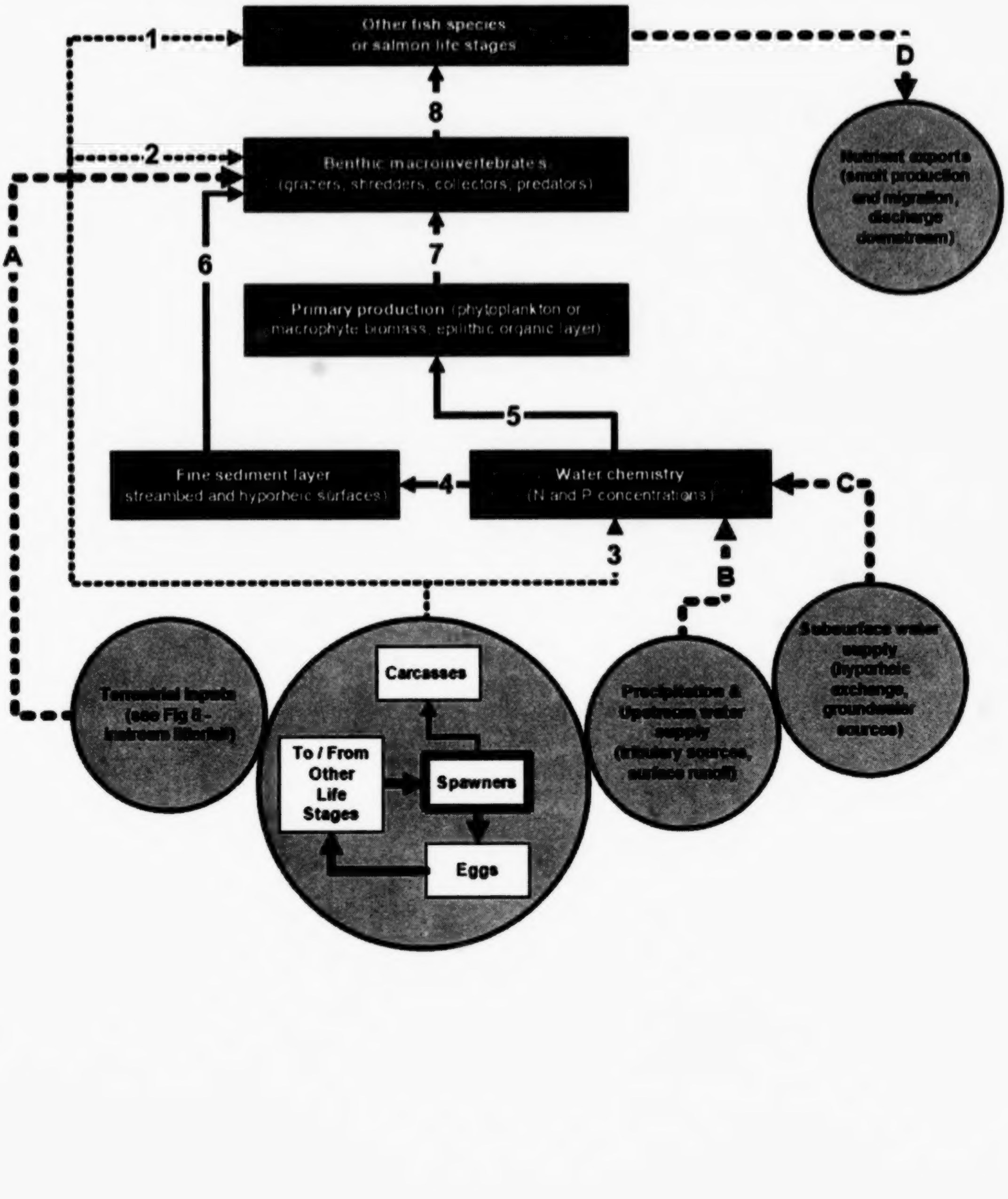

Other fish species or salmon life stages
1
D
8
2
Benthic macroinvertebrates (grazers, shredders, collectors, predators)
Nutrient exports (smolt production and migration, discharge downstream)
A
6
7
Primary production (phytoplankton or macrophyte biomass, epilithic organic layer)
5
Fine sediment layer (streambed and hyporheic surfaces)
4
Water chemistry (N and P concentrations)
C
3
B
Terrestrial inputs (see Fig 8 - instream litterfall)
Carcasses
To / From Other Life Stages
Spawners
Eggs
Precipitation & Upstream water supply (tributary sources, surface runoff)
Subsurface water supply (hyporheic exchange, groundwater sources)

Figure 7. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Stream Ecosystems.*

Thin dashed lines 1–3 represent direct links between spawners, carcasses, or eggs and some other ecosystem components (black boxes), while thin solid lines 4–8 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to/from stream environments. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect stream ecosystems by their actions. See Table 3 and Appendix A for details regarding the nature of these linkages and supporting literature sources.

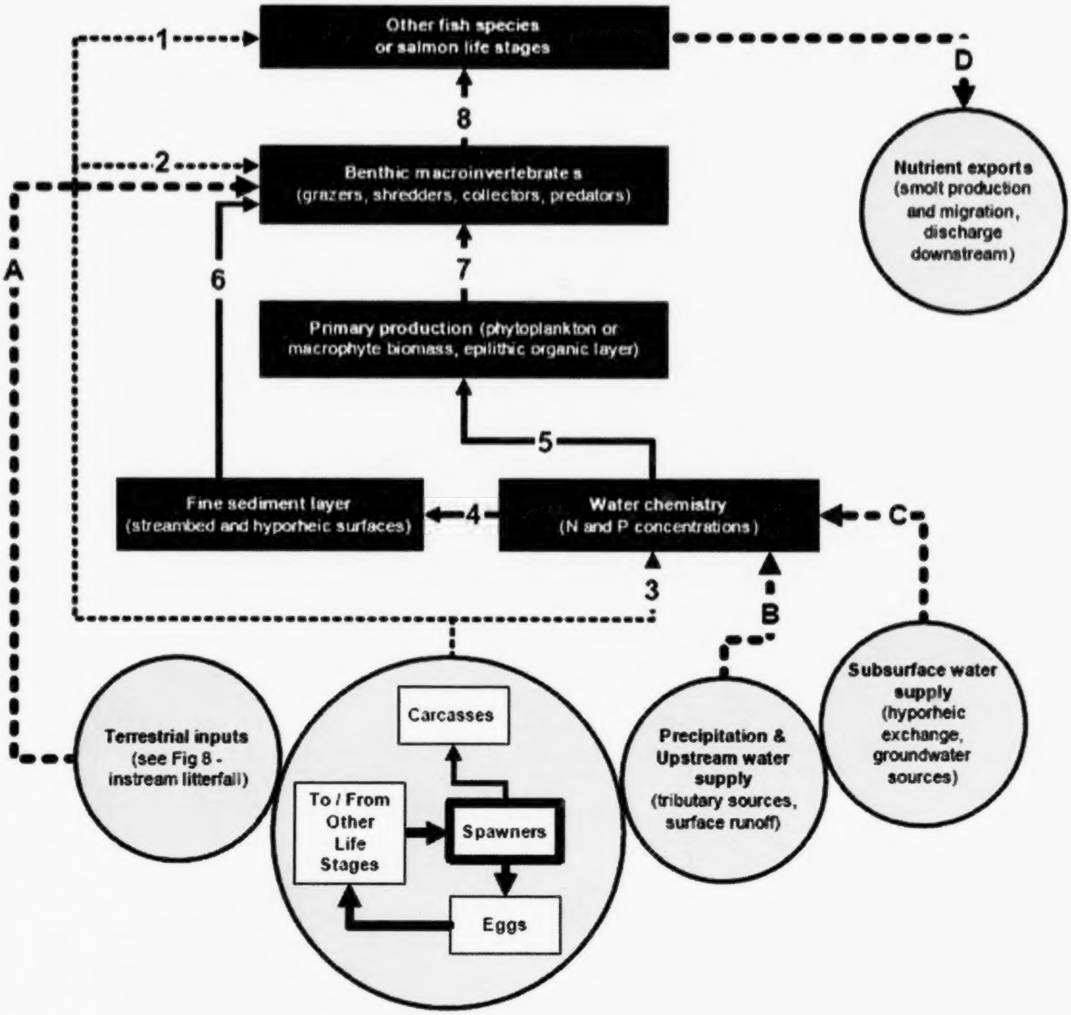

1
Other fish species or salmon life stages
D
8
Nutrient exports (smolt production and migration, discharge downstream)
2
Benthic macroinvertebrates (grazers, shredders, collectors, predators)
A
6
7
Primary production (phytoplankton or macrophyte biomass, epilithic organic layer)
5
Fine sediment layer (streambed and hyporheic surfaces)
4
Water chemistry (N and P concentrations)
C
3
B
Terrestrial inputs (see Fig 8 - instream litterfall)
Carcasses
To / From Other Life Stages
Spawners
Eggs
Precipitation & Upstream water supply (tributary sources, surface runoff)
Subsurface water supply (hyporheic exchange, groundwater sources)

Table 4. Description of the links related to *Nutrient Cycling in Riparian Vegetation* (Figure 8).
Evidence and references are provided in Appendix A. MD = marine-derived.

Link no.	Brief description of link
1	Nutrients from salmon are transferred to riparian and terrestrial predators through direct consumption of live spawners or carcasses. (What differentiates the latter from Link 2 is the nature of the consumer; Link 1 covers all consumption of salmon by predator species, even in cases where those species are exhibiting scavenging behaviour.)
2, 3	Nutrients from salmon are transferred to scavengers in two ways; they may be the first consumers of salmon carcasses once the spawners die (link 2), or may be scavenging carcass remnants left by predators (link 3).
4, 5	Predators (link 4) and scavengers (link 5) facilitate the transfer of nutrients to riparian and terrestrial soils and vegetation through several mechanisms: recycling, which includes decomposition and weathering and leaching of salmon tissues and bones from salmon or carcasses that they have picked up from lakes and streams and carried into the forest, and excretion (feces and urine) after feeding; and from insects that consume salmon tissue and then fly into riparian/terrestrial forests.
6	Heavy precipitation or snowmelt and associated floods may deposit salmon carcasses in the riparian areas, especially at sites where spawning coincides with periods of high discharge, providing nutrient input to riparian soils and vegetation when the carcasses decay.
7	Nutrients released from spawning salmon and from carcasses decomposing in the stream may be carried into the hyporheic zone beneath the riparian area; which then become available to the riparian vegetation where the roots of the plants extend into the hyporheic zone.
8	Over time, salmon-derived nutrients incorporated by riparian plants by any of the means described above can also move progressively further from the spawning stream by litterfall or by direct root transfer.
9	Fertilization of riparian vegetation by salmon-derived nutrients may enhance riparian productivity, thereby enhancing benefits that riparian vegetation provides to in-stream habitat though shading, sediment filtration and production of large woody debris. Increased N in riparian foliage increases litterfall rates and enhances the nutritional quality of litter delivered to the stream. There may be a positive feedback mechanism by which nutrients from salmon transferred to riparian vegetation helps improve spawning and rearing habitat for subsequent salmon generations.
10	Salmon-derived nutrient subsidies to terrestrial soil and vegetation may in turn affect a range of other components in these terrestrial systems.
11	Salmon-derived nutrients leach into soils via the pathways described above.
12	Salmon-derived nutrients can amplify at multiple trophic levels, from indirect food-web effects (rather than from direct consumption).

Figure 8. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Riparian Vegetation.*

Thin dashed lines 1 and 2 represent direct links between spawners or carcasses and other ecosystem components (black boxes), while thin solid lines 4, 5, 10, and 12 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to / from terrestrial forests. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect riparian responses by their actions. See Table 4 and Appendix A for details regarding the nature of these linkages and supporting literature sources.

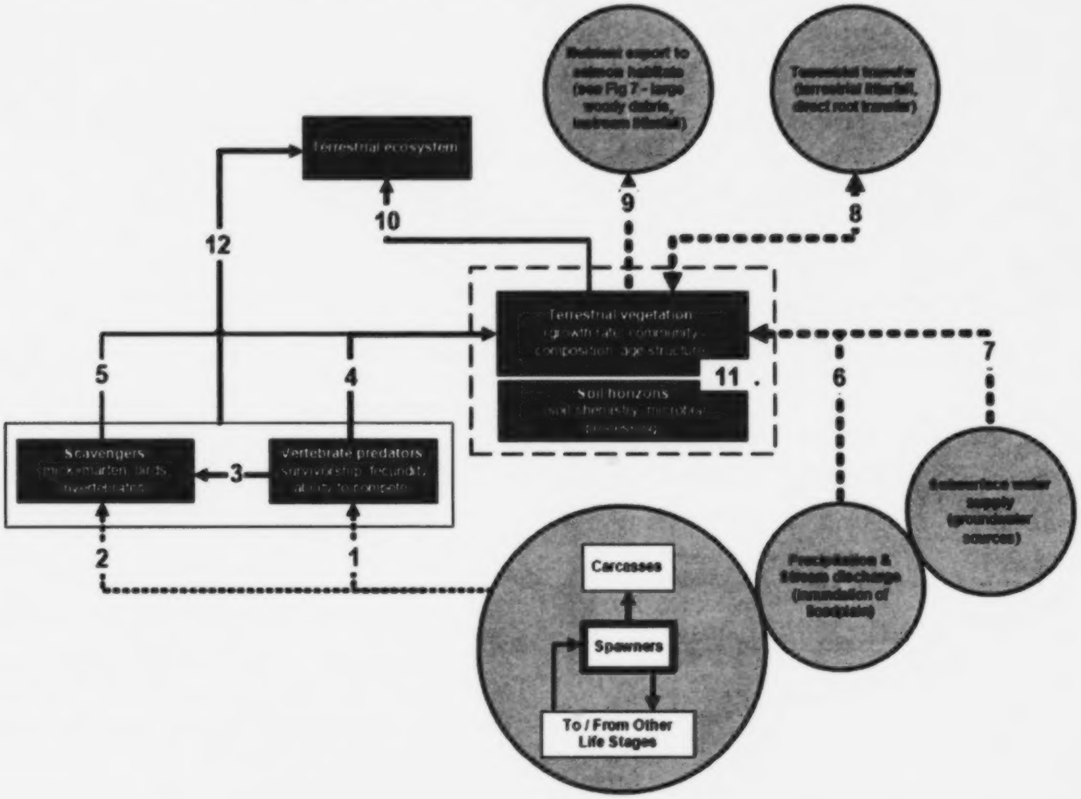
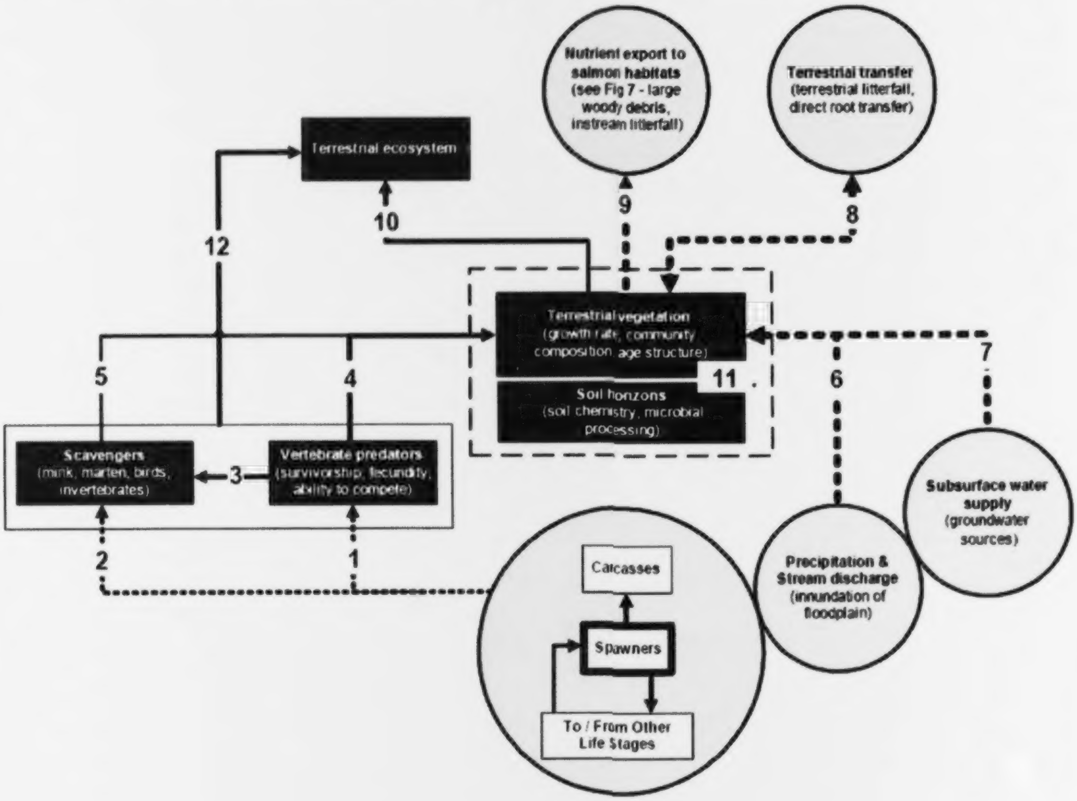

Nutrient export to salmon habitats (see Fig 7 - large woody debris, instream litterfall)
Terrestrial transfer (terrestrial litterfall, direct root transfer)
Terrestrial ecosystem
12
10
9
8
Terrestrial vegetation (growth rate, community composition, age structure)
11
Soil horizons (soil chemistry, microbial processing)
5
4
6
7
Scavengers (mink/marten, birds, invertebrates)
3
Vertebrate predators (survivorship, fecundity, ability to compete)
2
1
Carcasses
Spawners
To / From Other Life Stages
Precipitation & Stream discharge (inundation of floodplain)
Subsurface water supply (groundwater sources)

Figure 8. Conceptual diagram representing the linkages between salmon and *Nutrient Cycling in Riparian Vegetation.*

Thin dashed lines 1 and 2 represent direct links between spawners or carcasses and other ecosystem components (black boxes), while thin solid lines 4, 5, 10, and 12 represent indirect links. Circles (and dashed lines) represent the main imports and exports of nutrients to / from terrestrial forests. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect riparian responses by their actions. See Table 4 and Appendix A for details regarding the nature of these linkages and supporting literature sources.


Nutrient export to salmon habitats (see Fig 7 - large woody debris, instream litterfall)
Terrestrial transfer (terrestrial litterfall, direct root transfer)
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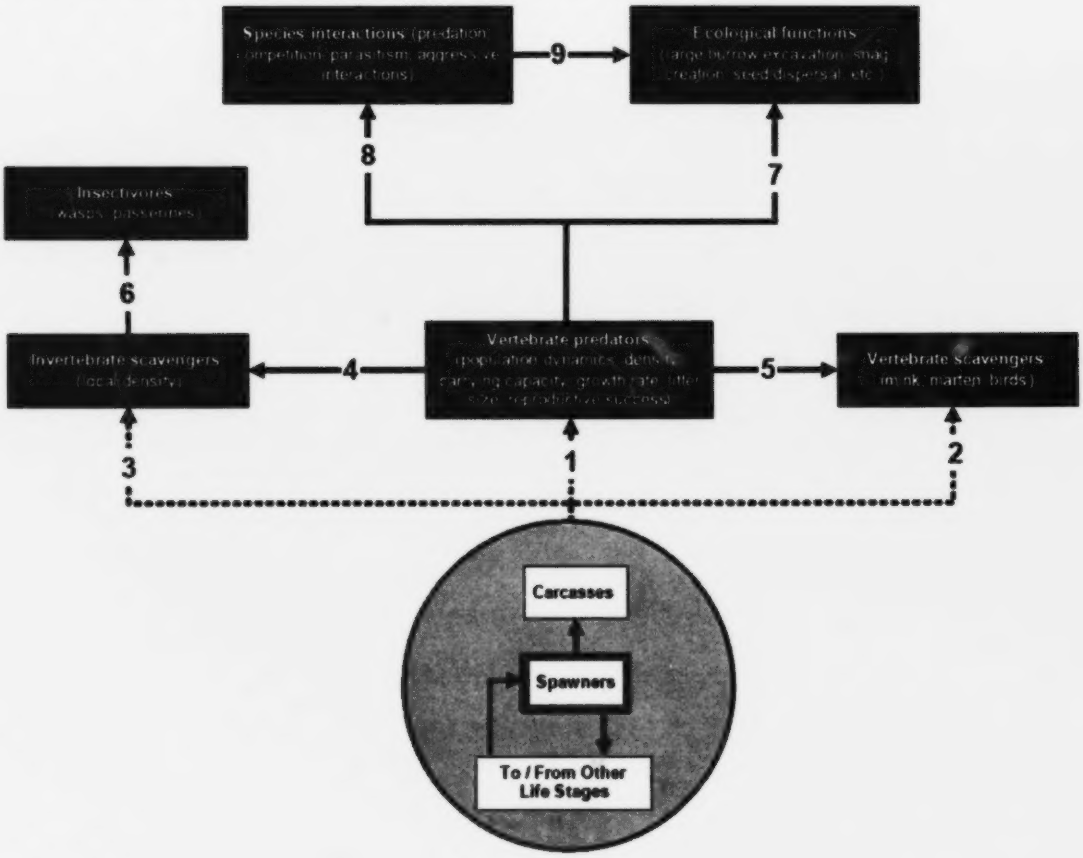
Soil horizons (soil chemistry, microbial processing)
5
4
6
7
Scavengers (mink, marten, birds, invertebrates)
3
Vertebrate predators (survivorship, fecundity, ability to compete)
Subsurface water supply (groundwater sources)
2
1
Precipitation & Stream discharge (inundation of floodplain)
Carcasses
Spawners
To / From Other Life Stages

Table 5. Description of the links related to *Food Source for Terrestrial Wildlife* (Figure 9).
Evidence and references are provided in Appendix A. MD = marine-derived.

Link no.	Brief description of link
1	This link represents direct consumption by vertebrate predators of both spawners and carcasses. Consumption of spawners provides food with higher energetic content than carcasses of senescent salmon, both for predators (link 1) and for scavengers (links 4 and 5) that follow.
2,3	Scavengers (vertebrate and invertebrate) directly consume carcasses of senescent salmon.
4, 5	Scavengers (vertebrate and invertebrate) consume carcasses of spawners killed and partially consumed by predators. This provides scavengers with several benefits over pathways 2 and 3: the food is of higher quality, it is available earlier in the season, and it is more accessible.
6	Energy and nutrient subsidies provided by salmon may influence food resources for insectivores by increasing the density of invertebrate scavengers.
7	Changes in the characteristics of vertebrate predator populations may affect a range of ecological functions that these species influence.
8, 9	Changes in the characteristics of vertebrate predator populations may affect interactions with other species such as predation by secondary consumers (species that prey on species that eat salmon), competition, parasitism, and other aggressive interactions.

Figure 9. Conceptual diagram illustrating role of salmon as a *Food Source for Terrestrial Wildlife*.

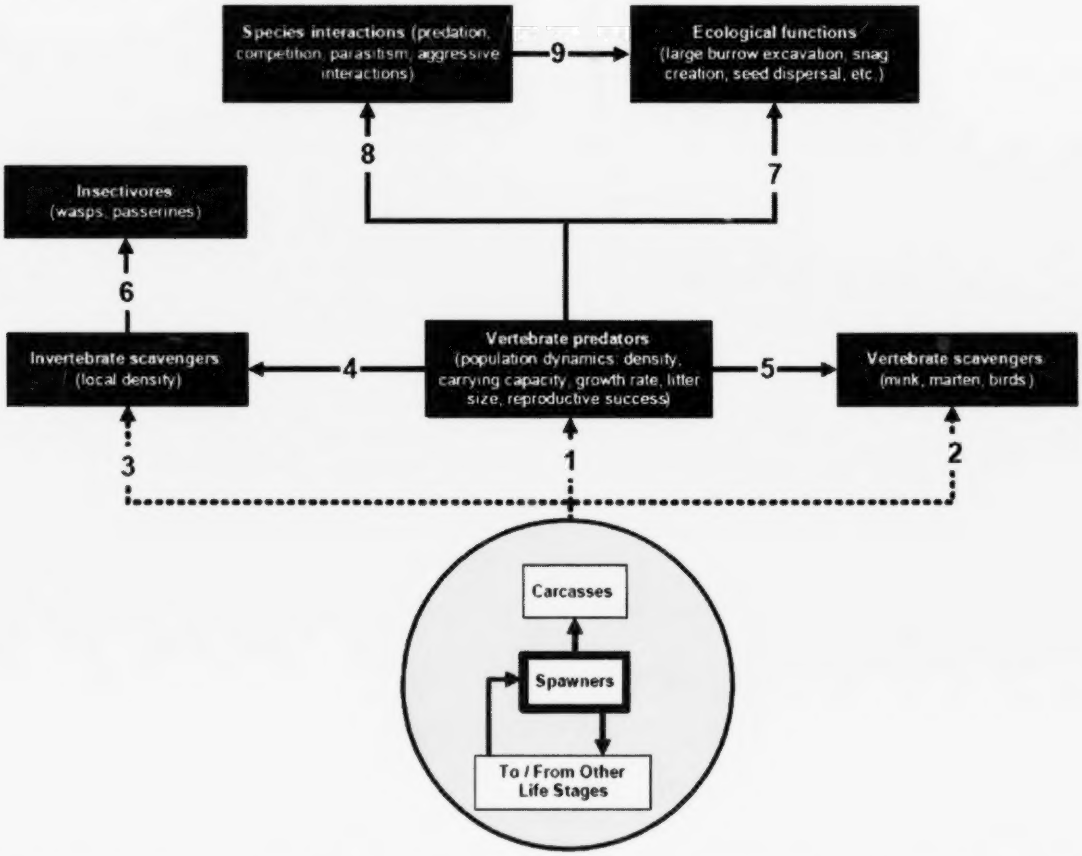
Thin dashed lines 1–3 represent direct links between spawners or carcasses and terrestrial wildlife (black boxes), while thin solid lines 4–9 represent indirect links. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect wildlife responses by their actions. See Table 5 and Appendix A for details regarding the nature of these linkages and supporting literature sources.


Species interactions (predation, competition, parasitism, aggressive interactions)
9
Ecological functions (large burrow excavation, snag creation, seed dispersal, etc.)
8
7
Insectivores (wasps, passerines)
6
Invertebrate scavengers (local density)
4
Vertebrate predators (population dynamics, density, carrying capacity, growth rate, litter size, reproductive success)
5
Vertebrate scavengers (mink, marten, birds)
3
1
2
Carcasses
Spawners
To / From Other Life Stages

The indicator themes and candidate indicators (see Table 6 and Appendix C) suggested in this report have emerged from our review of the literature and development of conceptual diagrams (Figures 6, 7, 8, and 9). Indicator themes represent general categories or subject areas that we believe would be useful at representing the various linkages between salmon and the broader ecosystem. The motivation for selecting indicators are based on the management questions discussed in Section III. Indicator themes may: (1) be important direct or indirect drivers of ecosystem responses (e.g., marine conditions affect salmon abundance); (2) help understand the effect of potentially confounding influences on ecosystem response (e.g., the role of agriculture, forestry, or waste management activities in masking the effect of nutrient contributions of salmon); or (3) provide direct measures of the linkage between spawner abundance and ecosystem response (e.g., response of macroinvertebrate communities to changes in escapement). Candidate indicators relate to the specific data that could be collected or models that might be used to represent the indicator themes.

Figure 9. Conceptual diagram illustrating role of salmon as a *Food Source for Terrestrial Wildlife*.

Thin dashed lines 1–3 represent direct links between spawners or carcasses and terrestrial wildlife (black boxes), while thin solid lines 4–9 represent indirect links. The "spawners" box (white box with thick outline) represents the primary mechanism by which managers would affect wildlife responses by their actions. See Table 5 and Appendix A for details regarding the nature of these linkages and supporting literature sources.


Species interactions (predation, competition, parasitism, aggressive interactions)
9
Ecological functions (large burrow excavation, snag creation, seed dispersal, etc.)
8
7
Insectivores (wasps, passerines)
6
Invertebrate scavengers (local density)
4
Vertebrate predators (population dynamics: density, carrying capacity, growth rate, litter size, reproductive success)
5
Vertebrate scavengers (mink, marten, birds)
3
1
2
Carcasses
Spawners
To / From Other Life Stages

The indicator themes and candidate indicators (see Table 6 and Appendix C) suggested in this report have emerged from our review of the literature and development of conceptual diagrams (Figures 6, 7, 8, and 9). Indicator themes represent general categories or subject areas that we believe would be useful at representing the various linkages between salmon and the broader ecosystem. The motivation for selecting indicators are based on the management questions discussed in Section III. Indicator themes may: (1) be important direct or indirect drivers of ecosystem responses (e.g., marine conditions affect salmon abundance); (2) help understand the effect of potentially confounding influences on ecosystem response (e.g., the role of agriculture, forestry, or waste management activities in masking the effect of nutrient contributions of salmon); or (3) provide direct measures of the linkage between spawner abundance and ecosystem response (e.g., response of macroinvertebrate communities to changes in escapement). Candidate indicators relate to the specific data that could be collected or models that might be used to represent the indicator themes.

Table 6 summarizes our suggested indicators themes, as related to three management questions. This table only discusses our rationale for recommending indicator themes rather than the specific indicators because there are many different ways to represent a theme by an indicator, some of which might not have been captured in our review. For example, sea surface temperature, Pacific Decadal Oscillation, El Nino-Southern Oscillation, Coastal Upwelling Indices, or an Oyster Condition Indicator might be useful to represent changes in marine conditions as relevant to Pacific salmon. At this stage of indicator development, the important emphasis should be on identifying whether the indicator themes will help address the management questions, though we recognize that the representation of a theme will depend highly on the specific indicator that is used. Appendix C provides a list of candidate indicators under each theme, as well as information on the type of monitoring required for each indicator and a qualitative rating of each indicator against the evaluation criteria listed in Section III.

This list represents the full range of candidate indicator themes that we believe are worth exploring, not necessarily the core list of indicators that should be integrated as part of Strategy 3. We anticipate that future efforts will be required to narrow this list, and the specific data or models used to inform them, to a more manageable number. Table 6 also lists priorities (high, medium, and low) for indicator development based on our assessment of the relevance of an indicator theme to managers, the level of scientific support, and the level of effort required to develop indicators further (e.g., data availability).

Table 6. Summary of the suggested indicator themes, indicators, and priorities, including a brief rationale for the recommendation.

Type I Indicators

Relevant management question	Indicator theme	Candidate indicators	Rationale for the theme	Priority
Type I Indicators—Which factors affect spawner abundance?	marine conditions	sea surface temperature (SST) Pacific Decadal Oscillation (PDO) El Nino-Southern Oscillation (ENSO) Coastal Upwelling Indices Oyster Condition Indicator	Marine conditions affect salmon growth and survival rates which will ultimately affect levels of escapement. Hence, salmon-ecosystem targets may vary depending on the anticipated productivity of the marine environment.	Low
	harvest rate	catch accounting	This indicator would include estimates of First Nations catch monitoring, commercial catch estimates, and recreational harvest. The indicator is the key management lever that will control escapement and potential influences on terrestrial and freshwater ecosystems. It is critical to discuss escapement goals (and related ecosystem effects) in the context of setting harvest rates (i.e., socio-economic indicators will be important considerations).	High
	implementation uncertainty	difference between management target and realized target	Important to identify potential biases when implementing management targets to help managers successfully achieve their ecosystem objectives.	Medium
	stock abundance	abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) escapement estimates (NuSEDs)	Estimates of stock abundance are critical for salmon management and understanding how changes in spawner abundance may affect the broader ecosystem. Year to year variation in salmon abundance may also have important implications to ecosystems.	High
	enroute mortality	discharge estimates of enroute mortality water temperature disease incidence / virulence	Environmental sources of enroute mortality (e.g., water temperature and discharge) will most likely adjust in-season estimates of abundance and the number of spawners anticipated on the spawning grounds. Additional work may be necessary to clearly understand the effect of these factors on escapement.	Low
	abundance of predators	abundance of osprey, bald eagle, black bear, grizzly bear, and northern river otter in freshwater environments, as well as harbour seals and sea lions in the marine environment	As detailed by the linkages described in Figure 9, terrestrial salmon predators will also influence spawner abundance. However, the nature and strength of these linkages on controlling salmon abundance is unclear. Predation of salmon in the marine environment is another pathway that may also affect spawner abundance (NMFS 1997).	Low

Table 6. Summary of the suggested indicator themes, indicators, and priorities, including a brief rationale for the recommendation.

Type I Indicators

Relevant management question	Indicator theme	Candidate Indicators	Rationale for the theme	Priority
Type I Indicators—Which factors affect spawner abundance?	marine conditions	sea surface temperature (SST) Pacific Decadal Oscillation (PDO) El Nino-Southern Oscillation (ENSO) Coastal Upwelling Indices Oyster Condition Indicator	Marine conditions affect salmon growth and survival rates which will ultimately affect levels of escapement. Hence, salmon-ecosystem targets may vary depending on the anticipated productivity of the marine environment.	Low
	harvest rate	catch accounting	This indicator would include estimates of First Nations catch monitoring, commercial catch estimates, and recreational harvest. The indicator is the key management lever that will control escapement and potential influences on terrestrial and freshwater ecosystems. It is critical to discuss escapement goals (and related ecosystem effects) in the context of setting harvest rates (i.e., socio-economic indicators will be important considerations).	High
	implementation uncertainty	difference between management target and realized target	Important to identify potential biases when implementing management targets to help managers successfully achieve their ecosystem objectives.	Medium
	stock abundance	abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) escapement estimates (NuSEDs)	Estimates of stock abundance are critical for salmon management and understanding how changes in spawner abundance may affect the broader ecosystem. Year to year variation in salmon abundance may also have important implications to ecosystems.	High
	enroute mortality	discharge estimates of enroute mortality water temperature disease incidence / virulence	Environmental sources of enroute mortality (e.g., water temperature and discharge) will most likely adjust in-season estimates of abundance and the number of spawners anticipated on the spawning grounds. Additional work may be necessary to clearly understand the effect of these factors on escapement.	Low
	abundance of predators	abundance of osprey, bald eagle, black bear, grizzly bear, and northern river otter in freshwater environments, as well as harbour seals and sea lions in the marine environment	As detailed by the linkages described in Figure 9, terrestrial salmon predators will also influence spawner abundance. However, the nature and strength of these linkages on controlling salmon abundance is unclear. Predation of salmon in the marine environment is another pathway that may also affect spawner abundance (NMFS 1997).	Low

Type II Indicators

Relevant management question	Indicator theme	Candidate Indicators	Rationale for the theme	Priority
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values?	human disturbance (forestry, agriculture, effluent sources)	area of agricultural activity watershed area with forest harvesting location of point source discharges	Inputs of nutrients from human development activities may also affect ecosystem responses. It is important to understand the role of these contributions relative to salmon sources.	High
	restoration activities	lake fertilization stream fertilization carcass enhancement forest fertilization	Nutrient enhancement programs will affect nutrient loadings into freshwater and terrestrial environments and their related ecosystems.	High
	watershed / ecosystem characteristics	elevation BEC stream geomorphology groundwater EAU BC	Watershed or terrestrial ecosystem attributes affect water quality (including nutrients), as well as salmon habitats. Classification of watersheds, stream, and lakes by such variables may help identify those areas where salmon will have the greatest influence on freshwater and terrestrial ecosystems.	Medium
	hydrology	discharge lake flushing rate annual precipitation watershed drainage area	Stream discharge and lake flushing rates will affect nutrient concentrations and the relative importance of marine-derived nutrients.	High
	vegetation cover	BEC length of stream with riparian harvesting riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)	Vegetation cover affects litterfall inputs of nutrients into streams, while nitrogen fixing plants affect terrestrial and freshwater nutrient cycles.	Medium
	bedrock geology	classification of bedrock geology	Important factor that influences water quality. May be considered as part of EAU BC classifications.	Medium
	microbial processing	uncertain	Microbial processes may preferentially fix nitrogen altering natural isotope ratios and potentially fixing nitrogen in nutrient limited areas so it is unavailable to other elements of the ecosystem.	Low

Relevant management question	Indicator theme	Candidate Indicators	Rationale for the theme	Priority
	water quality / chemistry	N concentration (nitrate, nitrite, ammonia) P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) acidity (pH), alkalinity water temperature Total dissolved solids (TDS)	Information about the ambient concentration of nutrients is critical to understanding the relative importance of nutrient sources from salmon. Other water quality variables may be reasonable surrogates of nutrient concentrations.	High
	spawner abundance	escapement estimates (NuSEDs) historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	Estimates of current and historical abundance are critical to identifying those areas where salmon may provide the greatest benefits—maintain salmon in areas where they are critical and restore salmon in areas where they were historically important to the ecosystem. Year to year variation in salmon abundance may also have important implications to ecosystems.	High
	salmon distribution	fish distribution mapping	Use current (and historic) spatial distribution of salmon to help prioritize those areas where managers should focus their efforts to enhance ecosystems.	High
	distribution of predators	distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	Distribution of predators will provide some basis to select areas where increasing spawner abundance will benefit terrestrial food webs and terrestrial nutrient cycling. Vertebrate predators provide the most direct link to terrestrial vegetation, are the links for with the most evidence, and the links that drive many other pathways. Focus on watersheds having populations of these predator species, which are known to have a strong, consistent relationship. Many factors affect distribution and abundance of terrestrial species praying on salmon. It would be challenging to design a monitoring program that would account for other potentially confounding factors and allow for detection of a reliable cause-effect signal from changes in spawners. Because of the strong, consistent relationship to salmon, these species may provide the best opportunities for detecting such changes.	High
	abundance of predators	abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter		High

Type III Indicators

Relevant management question	Indicator theme	Candidate indicators	Rationale for the theme	Priority
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems?	water quality / chemistry	N concentration (nitrate, nitrite, ammonia) P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)	Most evidence about effects of MD nutrients on ecosystem components (e.g., other trophic levels) is represented by studies demonstrating statistical correlations. Hence, there are cautions when interpreting these results. Experimental manipulations of entire ecosystems are needed to develop defensible and quantifiable relationships that can be used to establish escapement goals. Few studies provide this type of guidance, especially as relevant to BC. In either direct or indirect ways, all of these Type III indicators have been related to salmon, as illustrated by Figures 6–9 and described in Tables 2–6 and Appendix A. We envision a subset of these indicators being part of an experimental design or structured monitoring and evaluation design to better understand ecosystem responses to changes in spawner abundance (see recommendations in Section V).	Low
	primary productivity	algal (blue-green algae), macrophyte, and/or phytoplankton biomass chlorophyll a diatom biomass (or community diversity)		Low
	secondary productivity	zooplankton biomass (or community diversity)		Low
	macroinvertebrate production	index of biological integrity (IBI) invertebrate biomass (or community diversity)		Low
	juvenile fish production (other species and/or salmon life stages)	salmon smolt abundance juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) juvenile weight		Low
	timing of stock migration	migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	Timing of spawning and thus the timing of delivery of marine-derived nutrients or food sources may be critical. Importance may depend on how spawning coincides with the timing of ecosystem needs for those nutrient or food subsidies.	Low
	sediment layer	analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)		Low
	fine sediment layer	uncertain		Low

Relevant management question	Indicator theme	Candidate Indicators	Rationale for the theme	Priority
	vegetation	foliar N and ^{15}N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m^2/ha/yr])	Changes in riparian and terrestrial vegetation have been strongly related to changes in salmon-derived nutrients, thereby providing the best opportunities to track vegetation responses. These specific parameters seem to show the most reliable response of terrestrial vegetation to salmon-derived nutrients. Tree growth is a relatively easy parameter to measure, relative to foliar N and δ^{15}N. Note this delta symbol refers to tissue ^{15}N levels as measured relative to atmospheric levels (defined as zero), which is considered a universal standard. Greatest challenge may be that few monitoring programs currently collect these data.	Low
	wildlife	^{15}N of bear fur density and abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	Strong evidence of the importance of salmon in the diet of bears; and the strong, consistent relationship of all of these species to salmon.	Low
	riparian insects	^{15}N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	Strong evidence relating salmon spawning density and ^{15}N enrichment in riparian insects, including herbivorous and carnivorous Carabidae.	Low

V. RECOMMENDED NEXT STEPS

This section provides several suggestions to help those engaged in developing and implementing Strategy 3 of the Wild Salmon Policy (WSP). These recommendations relate to the three ideas, presented in Section II, that developers of the WSP need to address:

1. Clearly identifying the ecosystem values, resultant ecosystem objectives and suite of representative ecosystem indicators;
2. Deciding upon a suitable range of responses within which to maintain ecosystem indicators; and
3. Determining sufficient levels of escapement to maintain ecosystem responses within a suitable range.

Recommendation 1 clearly ties to point 1 above, while recommendations 2–6 provide alternative ways of better understanding the quantitative relationships between spawner abundance and the ecosystem indicators of interest. They would assist managers in addressing points 2 and 3 above.

Recommendation 1: Specify ecosystem objectives and benchmarks

There are two elements to this recommendation. The first is driven by the intent of Strategy 3 of the WSP, and addresses the need to specify the "ecosystem" values and developing ecosystem objectives that align with these values. The second is related, but more technical, and addresses the need to specify these ecosystem objectives as specific benchmarks against which indicator trends will be assessed.

Ecosystem Objectives

Ecosystem values, and ecosystem objectives that reflect these values, have not yet been specified, yet these are critical for proceeding, as they are at the heart of Strategy 3 and should drive the final indicator selection (as illustrated by the top box in Figure 5, and implied by the second evaluation criterion in Table 1 under Management Relevance: *relative importance*). This will not be an easy process, nor will it be purely scientific. Similar to the concept of "desired future states" that is being considered in other indicator initiatives (including the development of a draft Canadian Biodiversity Index led by Environment Canada), identifying ecosystem objectives will need to take into consideration a range of ecological, social and economic factors that reflect the interests of government, First Nations, stakeholders (particularly the conservation sector which championed the inclusion of Strategy 3 in the WSP) and the public. The process should be informed by scientific knowledge, traditional knowledge, and sustainable visions for the future.

Benchmarks

Benchmarks and management endpoints provide a contextual anchor for interpreting the monitoring results. Once identified, the ecosystem objectives should be translated into indicator benchmarks: specific quantitative threshold values or ranges (reflecting natural ecosystem dynamics and variability) for each indicator, which will allow for measurement of progress towards the objectives. For example, if one of the ecosystem objectives is to increase the health of riparian forests, and one of the chosen indicators is the rate of tree growth, then the benchmark for this indicator would be a specific growth rate that would signal success in achieving that objective. The benchmark for each indicator will likely represent a compromise between ecosystem conservation goals and other societal objectives, and should be established with the knowledge of some historic baseline state of the indicator (if known) for reference, recognizing that in many cases they will be different from an historic baseline.

Recommendation 2: Establish a basis for identifying variation in ecosystem response

A large body of research has shown that the structure of freshwater ecosystems can be dramatically altered by the presence of salmon spawners, resulting in a widely accepted paradigm that marine-derived nutrients (MD) from returning adult salmon increase freshwater productivity (as noted in Chaloner et al. 2004). However, the importance of spawning salmon in determining the productivity of freshwaters could vary considerably depending on factors such as the magnitude, timing, and distribution of spawning runs, carcass retention capacity, nutrient storage capacity, water temperature and discharge, background inputs of nutrients and allochthonous organic matter, and the composition of the biological community (Wipfli et al. 1999). The interaction of these factors probably produces broad variation in the biotic responses to salmon spawners across the Pacific Northwest (Chaloner et al. 2004). Resource managers developing restoration strategies for salmon in the Pacific Northwest will therefore need to consider how the conditions of individual catchments can modulate the influence of nutrient enrichment on freshwater ecosystems.

To fully assess the biological importance of salmon-derived nutrients, we must therefore not only know the magnitude, composition, and variability of salmon spawner inputs, but also the specific attributes of the watershed receiving them (Gende et al. 2002). The Ecological Aquatic Units for British Columbia (EAU BC) classification, in current development by the Nature Conservancy of Canada (NCC) in collaboration with the BC Ministry of the Environment (MOE), is intended to provide a consistent landscape template that could be used to structure broader analyses of watershed response to salmon nutrient inputs. According to recent unpublished NCC literature EAU BC will be a spatially explicit, hierarchical, freshwater ecological classification system designed to:

- Enable regional comparisons of freshwater ecosystems;
- Help inform species/habitat relationships through extrapolation of habitat data or species site information to other sites of the same EAU BC class;
- Provide a stratification framework for freshwater inventory/monitoring programs and state of the environment reporting; and
- Provide an important tool in the management of freshwater resources such as the development of management objectives and standards for specific freshwater ecosystem types.

EAU BC is intended to capture environmental features and processes defining variability in BC's freshwater ecosystems at three spatial scales: (1) ecological drainage units; (2) rivers ecosystems; and (3) lake and stream reach ecosystems. It is intended to be analogous to that of the provincial EcoRegion Classification System presently in place for terrestrial ecosystems. EAU BC will be packaged as a digital map and database information system (GIS) so that the classification data (key environmental factors and ecosystem types), can be queried and viewed at multiple spatial scales. Freshwater ecosystems classified as the same ecosystem type are expected to share similar physical environments and ecological processes, similar environmental and economic values, and similar responses to human disturbance despite the possibility that they are geographically separated. This proposed hierarchical freshwater ecological classification framework is intended to provide a critical and necessary foundation for understanding freshwater ecosystems and their associated biodiversity within BC and determining critical priorities for freshwater biodiversity conservation and management. The NCC/MOE recognize that EAU BC is currently a series of hypotheses that needs to be tested and refined through rigorous groundtruthing and expert review, and that it is vulnerable to the type, resolution, and overall quality of available spatial data that informs it. It is anticipated that data will be gathered concurrently to refine/test the classification as it is developed for use by Provincial Ministries and other partner organizations.

Recommendation 3: Conduct extensive comparisons across multiple watersheds

We recommend that as the provincial framework of EAU BC becomes established and internally validated, existing biological datasets should be explored opportunistically to clarify the linkages between physical processes at different scales (as captured by EAU BC) and varied biological responses relating to nutrient enrichment. Recent unpublished work by R. Ptolemy (2005) suggests that exploring such landscape level classifications may have considerable management utility. Employing the cruder terrestrial-based provincial ecoregional classifications for characterizing streams, Ptolemy found that EcoSections and EcoProvinces could be used to distinguish streams' basic water chemistry and runoff, and that these differences could be used to predict the biomass of resident salmonids (coastal cutthroat trout and Dolly Varden). He also found that parr density benchmarks initially established for these species in the different EcoSections were greatly exceeded where streams had been enriched (e.g., by large numbers of spawning pink salmon). Unpublished work by Parkinson et al. 2004 also showed that different provincial biogeoclimatic zones display quantifiable differences in lake productivity (e.g., TDS) and pH related to differences in zonal temperature and precipitation regimes, and these were reflected in predictable differences in densities and growth rates of rainbow trout. Continuing such analytical approaches in conjunction with the more accurate aquatic classifications being developed for EAU BC could allow valid identification of areas across BC where salmon are, or could be, most critical in influencing ecosystem structure, composition or function (Type II questions) i.e., where are the specific areas that are most nutrient limited and most salmon-dependent?

EAU BC should also provide the spatial stratification of provincial watersheds likely necessary to cost-effectively frame questions about ecosystem response to nutrient inputs from returning spawners and progress towards ecosystem goals (Type III questions). Where historical biological data exist across gradients of nutrient supply and salmon abundance, this could provide opportunities for broad scale analyses of indictor responsiveness. Going forward, it would be valuable to examine proposed monitoring locations for their potential benefit in development of ecosystem indicators.

Recommendation 4: Conduct large-scale field experiments

Most evidence about effects of MD nutrients on ecosystem indicators is represented by observational studies demonstrating statistical correlations (e.g., Naiman et al. 2002). Hence, there are cautions when interpreting these results; large scale experimental manipulations of lakes/streams/watershed would be much more useful (e.g., Carpenter et al. 1995; Schindler et al. 2000) in establishing causal mechanisms, but may be logistically difficult and relatively expensive to pursue. Such experiments will need to determine a reasonable set of core watershed and habitat covariates that can be used for matching treatment-control pairs (e.g., Marmorek et al. 2004) (a process which EAU BC should expedite) and then create significant contrasts between treatment (e.g., increased nutrient enrichment) and control replicates. Bayley (2002) cautions that proof of dominant cause and effect relationships operational at scales appropriate for a studied population may always be elusive (particularly when dealing with biological data), even with the best designed field experiments. However, validation monitoring approaches that aim for strong inference based on multi-stream, multi-lake or multi-watershed studies over time should provide valuable information (Bayley 2002; Marmorek et al. 2004).

We recommend the development of multi-watershed experiments to examine the influence of changes in spawner abundance, thereby addressing Type III questions. Such experiments should consistently apply the principles of experimental design articulated by McAllister and Peterman 1992. These design principles are:

1. Clearly state objectives, hypotheses, or questions of interest;
2. Properly identify the scope of the experiment (e.g., relevant spatial, temporal, and biological scales);
3. Use treatments and controls, or contrasting treatments;
4. Replicate treatments and controls;
5. Randomly assign treatments and controls to study units;
6. Allow sufficient sample size to detect ecologically significant effect sizes with sufficient statistical power;
7. Ensure complete measurement of relevant response variables; and
8. Provide effective monitoring of responses.

Since large-scale field experiments require intensive effort, it is sensible to build on locations where past work has created a foundation of data and knowledgeable investigators (e.g., Carnation Creek, Stuart-Takla, Keough River).

Recommendation 5: Conduct comprehensive status and trends monitoring

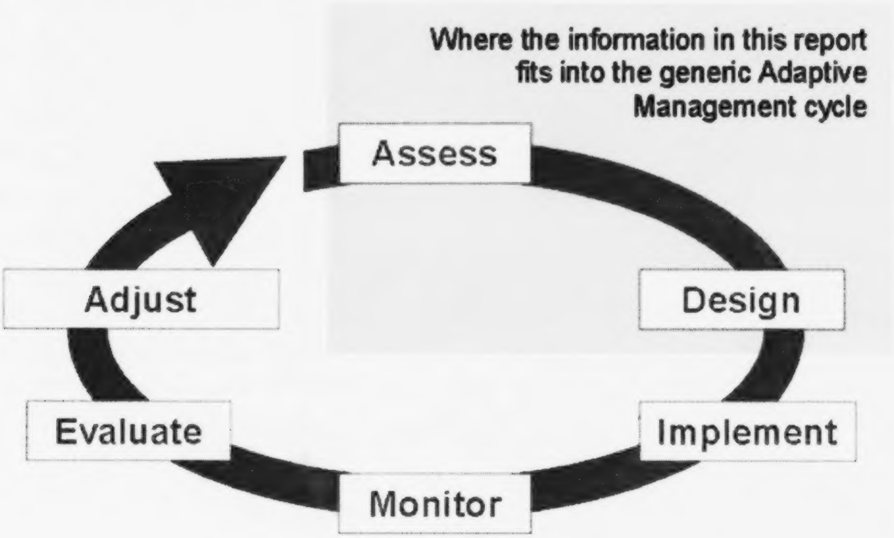
Final selection of core monitored indicators for addressing Type III questions will come from the process of continued review, experimentation and analyses of landscape/biology linkages through the steps described above (i.e., Recommendations 1–4). Once the final core indicators are selected, then broad monitoring of these indicators in the field should be based upon a probabilistic sampling design that can allow valid inferences across scales. In this regard, we suggest that Environmental Monitoring Assessment Program (EMAP) designs developed for aquatic resource monitoring by the US-EPA could be adopted and customized as necessary for sampling streams and lakes in BC. The EPA's Generalized Random Tessellation Stratified (GRTS) designs have been developed to ensure flexible, spatially-balanced, random selection of aquatic sampling sites, drawing from stratified GIS themes (as in EAU BC) to provide the spatial framework for the overall survey design. EMAP has been used most notably to design Oregon's current coastal coho monitoring program that provides statistically rigorous data about the status and trends of the state's coho populations and their habitat at multiple spatial scales. To our knowledge EMAP has not yet been employed for sampling programs in Canada but has become the recommended standard for probabilistic sampling design in the U.S. Pacific Northwest (PNAMP 2005).

Recommendation 6: Use an adaptive management approach

We recommend that implementation of Strategy 3 of the WSP requires a management system with an explicit commitment to **learning** (Figure 10)—a basic principle of adaptive management. This suggestion implies several things, the most important being the need to be very clear about what is meant by "ecosystem values," and being able to translate them into measurable ecosystem objectives. In other words, quantitative indicators need to be identified and measured to evaluate the success with which managers are achieving their objectives. For example, if biodiversity is considered to be an important ecosystem value under Strategy 3, what changes to biodiversity would we expect (or want) to see if the number of spawners were to increase? If the values cannot be put into quantitative terms, it will be difficult if not impossible to determine if new escapement targets set for ecosystem objectives are actually working. Some initial steps have been taken through this work to identify measurable ecosystem objectives.

A commitment to learning also implies explicitly recognizing key uncertainties (i.e., admitting what we don't know), making predictions about expected outcomes based on the best available knowledge, designing and undertaking monitoring sufficient to assess success against objectives, and using the results to inform subsequent management policy and actions as well as update the state of science. This transfer of knowledge about what has been learned to decision-makers is a key tenet of adaptive management, and it is important that the management and decision systems under the Wild Salmon Policy be receptive to what is learned through monitoring under Strategy 3, and make a commitment to using this information to inform their decisions (recognizing that other factors also need to be considered).

Figure 10. Six steps of adaptive management and alignment with this report.


Where the information in this report
fits into the generic Adaptive
Management cycle
Assess
Design
Implement
Monitor
Evaluate
Adjust

the success with which managers are achieving their objectives. For example, if biodiversity is considered to be an important ecosystem value under Strategy 3, what changes to biodiversity would we expect (or want) to see if the number of spawners were to increase? If the values cannot be put into quantitative terms, it will be difficult if not impossible to determine if new escapement targets set for ecosystem objectives are actually working. Some initial steps have been taken through this work to identify measurable ecosystem objectives.

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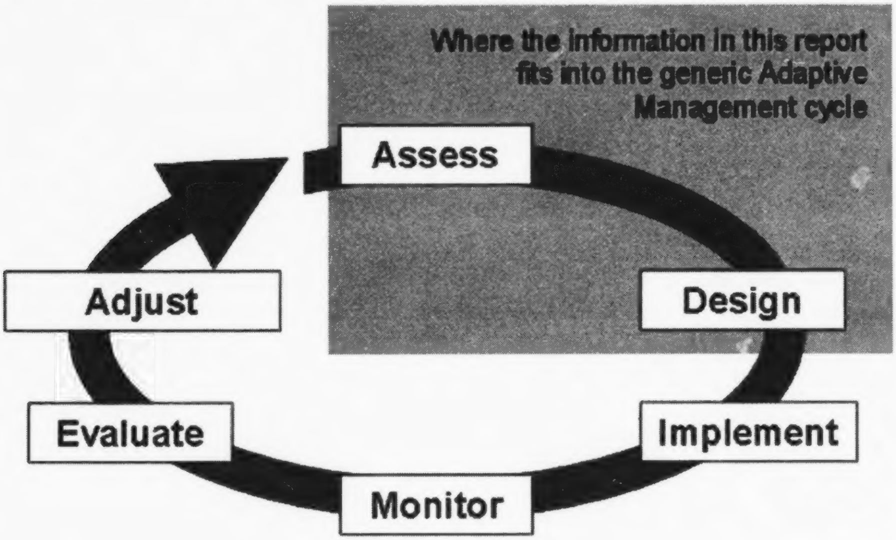
Where the information in this report fits into the generic Adaptive Management cycle
Assess
Design
Implement
Monitor
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Adjust

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APPENDIX A: TABLE DETAILING LINKAGES FROM THE CONCEPTUAL DIAGRAMS (FIGURES 1, 6–9)

Link and management relevance: Description of relevant cause-effect link (cross-reference to figure and linkage numbers). Is link directly or indirectly relevant to management decisions / questions (e.g., identifying priority management areas, establishing escapement goals)?

Evidence for: If important, supporting published literature, studies and/or observations.

Evidence against: Evidence that does not support the link.

Covariates or confounding factors: Other environmental / human factor(s) that influences response of VECs or some other link in the cause-effect pathway.

Critical uncertainties: What critical uncertainties may need to be addressed? What research, monitoring, modeling, or lit review could fill knowledge gaps and reduce uncertainties?

Data requirements: If appropriate, what variables should be measured or data should be collected? At what spatial / temporal scale? Who have these data?

Details of study / other comments: Note important information or caveats that do not fit under other headings.

Notes:

- **Direct link** between salmon spawners, carcasses, or eggs and some other ecosystem components (also see blue arrows in conceptual diagrams).
- **Indirect link** between salmon spawners, carcasses, or eggs and some other ecosystem components; link mediated by changes in some other ecosystem components.

Figure 1: General Salmon-Ecosystem Linkages

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–1] **Direct link** between survival of marine life stages and spawner abundance.	Mysak 1986; Mantua et al. 1997; Francis et al. 1998; Beamish et al 1999 as cited in Naiman et al. 2002 Drake et al. 2002		Short-term and long-term fluctuations in atmospheric and oceanic conditions affect marine productivity and salmon survival Harvesting	Exact mechanisms responsible for population changes in salmon are not fully understood	Require information pertaining to escapement surveys or carcass counts (spawner density) Pre-season and in-season forecasting models of abundance Indicator of marine conditions (e.g., SST) that incorporate geographic and temporal changes in marine productivity (though these could be integrated into forecasting models) Large-scale climatic effects may also affect freshwater ecosystems (e.g., changes in precipitation and snowpack, stream / lake temperatures)	Drake et al. 2002; Mysak 1986—short-term variability in climate conditions (e.g., ENSO) is apparent in dynamics of salmon and related ecosystems Beamish et al 1999; Francis et al. 1998; Mantua et al. 1997—strong evidence that decadal and longer modes of cyclical variability in marine ecosystems greatly influences growth and survival of Pacific salmon
[Fig 1–2] **Indirect link** between spawners (over-escapement) and number of recruits.	See linkages below [Fig 1–5] for possible mechanisms in streams and lakes	Walters et al. 2004	Effect of cyclic dominance on number of returning spawners. Effect of artificial enhancement (spawning channels, lake fertilization)—Walters et al. 2004	Effects on survival across all life stages included in Walters et al. 2004 analysis (e.g., enhanced juvenile survival due to changes in food production); could not disaggregate these effects		Walters et al. 2004—no evidence to indicate that over-escapement leads to stock collapse. However, analysis did note reduced spawner efficiency (i.e., fewer recruits per spawner).

Figure 1: General Salmon-Ecosystem Linkages

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–1] **Direct link** between survival of marine life stages and spawner abundance.	Mysak 1986; Mantua et al. 1997; Francis et al. 1998; Beamish et al 1999 as cited in Naiman et al. 2002 Drake et al. 2002		Short-term and long-term fluctuations in atmospheric and oceanic conditions affect marine productivity and salmon survival Harvesting	Exact mechanisms responsible for population changes in salmon are not fully understood	Require information pertaining to escapement surveys or carcass counts (spawner density) Pre-season and in-season forecasting models of abundance Indicator of marine conditions (e.g., SST) that incorporate geographic and temporal changes in marine productivity (though these could be integrated into forecasting models) Large-scale climatic effects may also affect freshwater ecosystems (e.g., changes in precipitation and snowpack, stream / lake temperatures)	Drake et al. 2002; Mysak 1986—short-term variability in climate conditions (e.g., ENSO) is apparent in dynamics of salmon and related ecosystems Beamish et al 1999; Francis et al. 1998; Mantua et al. 1997—strong evidence that decadal and longer modes of cyclical variability in marine ecosystems greatly influences growth and survival of Pacific salmon
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Figures 1 and 6: Salmon-Nutrient Links in Lake Ecosystems

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3] **Direct link** between spawners and contributions of MD nutrients to lake ecosystems. Carcasses can be a major component of nutrient budgets, especially as most nursery lakes are nutrient limited. Consumption of spawners by other fish species and insects, contribute to other trophic levels in lakes.	Donaldson 1967; Kline et al 1993; Krohkin 1975; Mathisen et al. 1988; Schindler unpublished as cited in Naiman et al. 2002 Stockner et al. 2000		Main factors affecting lake responses to nutrient changes (e.g., hydrology and relative loading of N and P from a watershed (Naiman et al. 2002)). Non-salmon nutrient sources (e.g., agriculture, nitrogen fixing plants). Factors affecting changes in primary and secondary productivity, as well as competition and predation with other species.	Links between MD nutrient fluxes and other lentic food web changes are relatively unexplored.	Need data to help understand ambient nutrient concentrations relative to historic levels with and without salmon (i.e., identify those areas where nutrients are a limiting factor) Indicators related to: *historic levels of spawner abundance (paleolimnological records) *hydrology (precipitation and drainage area) *relative nutrient loading from other sources (fertilization or agricultural activities)	Kline et al 1993; Mathisen et al. 1988; Schindler unpublished—isotope studies indicate MD nutrients are distributed through the food web with large sockeye runs
[Fig 1–5] **Direct link** between spawners and density dependent mortality due to increased risk of pre-spawn mortality. For example, in areas of difficult passage, such as several spots in the Fraser canyon, higher escapements could slow migrations down at certain flows (creating a logjam of fish) and thereby increasing enroute mortality (Gordon Ennis personal communication).	Discussed by Walters et al. 2004, though no evidence provided Gordon Ennis, personal communication.		Factors affecting enroute mortality (e.g., water temperatures, flow, incidence of disease)		Pre-spawning mortality rates. See Walters et al. 2004 report for some discussion about potential data sources.	
[Fig 1–5] **Indirect link** among spawners, juvenile salmon, and competition for food sources with other lake fish species. Increased number of spawners would result in a greater number of juveniles in lakes and possible exhaustion of available food resources. (e.g., changes in competition between rainbow and sockeye in Quesnel lake due to changes in spawner abundance).	Schmidt et al 1998; Kyle 1996 as cited in Naiman et al .2002 Discussed by Walters et al. 2004, though no evidence provided Jeremy Hume personal communication		Factors affecting fry survival and zooplankton production			Kyle 1996—modest stocking rates of juvenile sockeye in salmon barren AK lakes had substantial predation effects on zooplankton; community shifted to smaller-bodied organisms Schmidt et al. 1998—adult density of sockeye salmon had a strong negative effect on zooplankton biomass in response to higher fry densities

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 6–1] **Direct link** among spawners, MD-nutrients, and responses of lentic food web are relatively unexplored. Isotope studies indicate that MD-nitrogen is being transferred to resident fishes. Nutrient transfer results from the direct consumption of dead salmon tissue by fish, or via indirect links between spawners and lower trophic levels, e.g., uptake by primary producers [Fig 2–4,5,& 6]. There is mixed evidence regarding whether MD-nutrient inputs translates to higher capacity for nursery lakes to produce sockeye salmon.	Kline et al 1993; Mathisen et al. 1988; Schmidt et al. 1998; Schindler unpublished; Stockner and MacIsaac 1996 as cited in Naiman et al. 2002 Finney et al. 2000 Mazumder and Edmundson 2002		Factors that regulate changes in primary and secondary productivity as well as competition and predation with other species or salmon life stages. Growth and survival of juvenile sockeye positively related to temperature, food availability, and primary productivity (Naiman et al. 2002)	Mechanisms by which MD-nutrients move through benthic and pelagic food webs and consequences for ecosystem dynamics (Naiman et al. 2002). Evidence on trophic transfers limited to observational studies that only indicate that MD-nutrients are distributed throughout lentic food webs, not the mechanisms or processes for nutrient uptake and transfer. Few studies establish clear link between MD nutrient deposition and long-term recruitment of sockeye.	Indicators of MD-nutrients in higher trophic levels will not be very useful. Scientific understanding has not been developed well enough to provide strong rationale for selection of these types of indicators.	Finney et al. 2000—positive association between spawning density and MD-nutrient concentration in smolts. Kline et al 1993; Mathisen et al. 1988; Schindler unpublished—Isotope studies indicate MD nutrients are distributed through the food web with large sockeye runs. These are comparative studies looking at the distribution of MD-nutrients among ecosystem components. Schmidt et al. 1998—only study to establish clear link between MD nutrients and long-term recruitment of sockeye. Long-term reduction of sockeye substantially reduced P availability, thereby reducing primary and secondary productivity. Suggested that changes in P availability depressed production of sockeye populations Stockner and MacIsaac 1996—carcass deposition enhances rearing capacity of nursery lakes for juvenile sockeye Hume et al. 2004 (in Walters et 2004)—provides evidence that MD nutrients can translate into higher capacity for fish, though this story is complex. For example, in Shuswap Lake increased capacity does not seem to occur (which may be due to the Adams R. being near the lake exit and a loss of nutrients from the lake system); in Quesnel Lake, with the spawning area not near the lake exit, evidence suggested that MD nutrients can increase productivity of fish.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 6–2] **Direct link** between spawners and secondary production (zooplankton, invertebrates). Relationship is inconsistent. Increased number of spawners may increase secondary production as a result of direct consumption of salmon tissue by invertebrates, or indirectly from increased primary production [Fig 2–5]. Alternatively, there may be a negative relationship—increased predation on zooplankton biomass occurs due to a greater abundance of juveniles (counteracts the potential benefits from MD-nutrient fertilization).	*Positive relationship between spawners and secondary production* Mazumder and Edmundson 2002	*Negative relationship between spawners and secondary production* Krohkin 1975; Kyle 1996; Schmidt et al. 1998 as cited in Naiman et al. 2002 Mazumder and Edmundson 2002	See contrasting evidence	See contrasting evidence	Inconsistent relationship. Not useful as an indicator.	Krohkin 1975—decreases in primary production associated with low sockeye returns, translated to decreases in production of zooplankton and plankton eating fish (including sockeye) Kyle 1996—provides evidence of confounding effects of increased number of juveniles on zooplankton communities. Modest stocking rates of juvenile sockeye into barren lakes had substantial predation effects on zooplankton communities—shifts to smaller-bodies species Mazumder and Edmundson 2002—biomass and size of Daphnia and size of sockeye smolts responded positively to fertilization; while fry stocking produced dramatic declines in biomass and size of Daphnia and size of sockeye smolts Schmidt et al. 1998—adult density of sockeye has a strong negative effect on zooplankton biomass in the year following spawning
[Fig 6–4] **Indirect link** among spawners, water quality, and primary productivity in nutrient limited lakes. Nutrients from salmon carcasses have the potential to stimulate lake primary productivity. Link represents direct uptake of nutrients by primary production.	Goldman 1960; Gross et al. 1998; Hyatt and Stockner 1985; Krohkin 1975; Kyle 1996; Schmidt et al. 1998; Wurtsbaugh et al. 1997; as cited in Naiman et al. 2002 Gregory-Eaves et al. 2004		Factors controlling ambient nutrient concentrations in lakes.	Data demonstrating clear link between escapement and lake productivity are sparse (Naiman et al. 2002).		Krohkin 1975—showed that years of poor escapement resulted in 20% decrease in primary production Kyle 1996—AK lakes with salmon barriers have 33% lower P concentration than similar lakes with salmon; double the difference in phytoplankton standing stock Schmidt et al. 1998—showed correlation between total P concentration and salmon escapement in previous year, translating to increased phytoplankton biomass.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 6–7] **Indirect link** between spawners and MD nutrients in lake sediments—mediated by incorporation of MD-nutrients into the food web and settling out from water column (i.e., via different trophic levels)—dominated by settling of plankton, diatoms, or in situ production of benthic algae. Lake sediments represent an integrated chronology of information about inputs of MD-nutrients and historical lake productivity. Isotope analyses or analysis of changes in diatom communities can be used to reconstruct spawner abundance.	Finney 1998; Lajtha and Michener 1994 as cited in Naiman et al. 2002 Holtham et al. 2004 Gregory-Eaves et al. 2003 Gregory-Eaves et al. 2004 Finney et al. 2000		Other sources of MD-nutrients from watershed and / or atmosphere. Flushing rate of lake.		Paleolimnological analyses of sedimentary ^{15}N isotope provide a good indication of historical trends in lake productivity—requires analysis of lakes with low flushing rates. Need to adjust for lake area when considering relationship between sedimentary N and escapement (see Finney et al. 2000)	Holtham et al. 2004—diatom communities appear to respond more sensitively to fluctuations in salmon populations than stable isotope methods, provide other changes in trophic status are minor. Lajtha and Michener 1994—two-source mixing model estimates response of ^{15}N signature to changes in density of spawning salmon. Historical salmon escapements are not linearly related ^{15}N signatures in lake sediments.

Figures 1 and 7: Salmon-Nutrient Links in Stream Ecosystems

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3] **Direct link** between spawners and contributions of MD-nutrients to oligotrophic streams (to stream biota, such as other fish species or life stages, periphyton, or macroinvertebrates). Salmon are relatively rich in P compared to N (Naiman et al. 2002; Gende et al. 2002). Advent of stable isotope methods has established that salmon can make large contributions of nutrients and organic matter to streams (though N has a useable stable isotope, P does not). Uptake processes and storage of MD nutrients in stream ecosystem vary throughout the year. Retention mechanisms vary with latitude, climate, animal populations, vegetation cover, and stream geomorphology (Gende et al. 2002).	Bilby et al. 2001; Johnston et al. 1997; Kline et al. 1990; Richey et al. 1975 as cited in Naiman et al. 2002 Naiman et al. 2002 Bilby et al. 1996 Bilby et al 1998 Gresh et al. 2000 Stockner et al. 2000		Isotopic fractionation is associated with microbial processing of N, which will affect stable isotope ratios in plants and soils. Microbes preferentially process ^{14}N over ^{15}N, resulting in ^{15}N enriched substrates. Such processing varies by slope, elevation, soil texture, and moisture. Concern may not be relevant if N availability is limiting (i.e., all available N will be processed) (see Naiman et al. 2002). Either N or P availability may control primary production, which varies by geologic substrate (Thut and Haydu) and possibly by season (Fevold 1998). E.g., nitrogen-fixing plants (alders) may ensure sufficient delivery of N inputs to a stream. Proportion of MD-nitrogen in a stream directly related to density of fish spawning at a site, and inversely related to time since spawning.	Lag time and legacy of MD nutrients in salmon-influenced ecosystems. Few studies on ecosystem-scale alterations resulting from salmon, thus extrapolations from correlative studies is cautioned. Ecosystem responses to relatively recent declines in salmon may not be fully expressed due to long legacy of MD nutrients and cycling in salmon-influenced ecosystems (Naiman et al. 2002).	Biogeoclimatic zones may account for variations in microbial processing of N (accounts for elevation and moisture) Timing of nutrient subsidy will be important to determine effect on reliant ecosystem component (e.g., how does timing of nutrient subsidy coincide with timing of what ecosystem requires?) Concerns about long lag times and legacy of MD-nutrients in salmon-influenced ecosystems may warrant a precautionary approach to managing escapement targets for ecosystem benefits—use ecosystem indicators to be proactive and avoid irreversible impacts on freshwater and terrestrial ecosystems. Use of stable isotope analysis has been suggested as an indicator of "system saturation" for salmon management (Bilby et al. 2001)	Bilby et al. 1996—Evidence of long-term storage and delivery of MD-nitrogen. Cutthroat trout and coho salmon ^{15}N signatures indicated that nitrogen is coming from marine sources even though the timing of sampling did not coincide closely with timing of spawners (e.g., MD nitrogen signatures observed immediately prior to spawning for cutthroat, well after spawning for coho) Bilby et al. 1998—proportion of MD-nitrogen in juvenile coho and steelhead tissues increased significantly after the addition of carcasses in SW WA streams Gresh et al. 2000—analysis of historical records and current escapement indicate that just 6–7% of historical levels of MD nutrients are currently reaching rivers of the Pacific Northwest. Johnston et al. 1997—proportion of MD nitrogen in insects and juvenile fish increased with increasing # of sockeye spawners. This is a non-linear relationship, MD-nitrogen increasing rapidly at low spawning densities, increasing more slowly at high densities. Kline et al. 1990—observed large contrasts in % MD-nitrogen in SE AK streams—particularly for rainbow trout, periphyton, and caddisflies (75,30, & 50%), after pink spawning; nearly all MD-nitrogen was derived from spawners

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–5] **Indirect link** between spawners and bioturbation of stream environment (i.e., acting as ecosystem engineers). Digging can disturb channel topography that changes water-flow patterns and stream biota. Such alterations can impact physical habitats (reduce sediment accumulation), periphyton (reduce abundance of attached algae) benthic invertebrates (increasing drift rates), and salmon eggs (several hypotheses—increase interstitial water and oxygen flow, redd superimposition, or deplete oxygen supplies).	Discussed by Walters et al. 2004 Moore et al. 2004 Schindler et al. 2003		Factors affecting egg survival (e.g., water temp, sedimentation of stream).			Moore et al. 2004—noted that bioturbation reduced sediment accumulation on streambed, decreased algal biomass, and reduced invertebrate densities.
[Fig 1–5] **Direct link** between spawner abundance and increased stray rates which promote genetic diversity of salmon stocks.	Discussed by Walters et al. 2004, though no evidence provided.					
[Fig 7–1] **Direct link** between juvenile salmon or other fish species and consumption of flesh from carcasses, or eggs from spawners. Represents uptake of nutrients into trophic system via heterotrophic organisms. Positive influence of MD nutrients on growth of juvenile salmon may increase survival thereby increasing higher levels of deposition of MD nutrients (Bilby et al. 1996). As well, MD nutrients affect invertebrate production [Fig 3–2], which may benefit food availability for other fish species or salmon life stages [Fig 3–8].	Eastman 1996 as cited in Naiman et al. 2002 Bilby et al. 1996 Wipfli et al. 2003 Chaloner et al. 2002 Bilby et al. 1998 Hicks et al. 2005 Heintz et al. 2004 Wipfli et al. 2004	Wilzbach et al. 2005	Physical, chemical, or biological conditions that affect habitats for these fish species or life stages.		Heintz et al. (2004) suggest fatty acid and lipid class analysis may be useful for examining the effects of MD nutrients on juvenile salmonids.	Bilby et al. 1998—in SW WA, > 60% / > 90% of stomach contents of coho / steelhead consisted of salmon eggs and carcass flesh with coho spawners present. Carcass additions doubled growth rate of juvenile coho relative to stream with fewer carcasses. Eastman 1996—when available, salmon eggs or carcasses comprise the majority of the diet of stream-dwelling salmonids Wipfli et al. 2003—MD-nutrients increased growth rates of juvenile salmon and resident fish; increases in growth diminished with higher carcass loading. Wilzbach et al. 2005—total density and biomass of resident salmonids responded positively to canopy removal, but were not detectably affected by carcass additions.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 7–2] **Direct link** between aquatic invertebrates and uptake into trophic system via heterotrophic organisms. Uptake may occur via consumption of eggs or flesh from carcasses or via effect of marine nutrient subsidy on increased primary production [Fig 3–5] and related effect on invertebrate production [Fig 3–7].	Brusven and Scoggin 1969; Elliott and Bartoo 1981; Minakawa 1997; Nicola 1968; Piorkowski 1995 as cited in Naiman et al. 2002 Zhang et al. 2003 Yanai and Kochi 2005 Wipfli et al. 1998 Bilby et al. 1996 Chaloner et al. 2002 Chaloner et al. 2004 Hicks et al. 2005 Ito 2003 Winder et al. 2005	Chaloner et al. 2004	Density or biomass of aquatic invertebrates may be affected by abundance of juvenile salmon, which is regulated, in part, by the number of spawners. Effects of nutrient fluxes may not be obvious; community composition may shift. Stream temperature, background water chemistry, and light attenuation (Chaloner et al. 2004).		Consider a measure of macroinvertebrate biomass. Measure of benthic invertebrate biodiversity may not be reasonable or reliable; lots of other habitat variables (beyond nutrients) affecting invertebrate community structure	Bilby et al. 1996—macroinvertebrates enriched with MD nutrients (N and C) where coho spawners were present. Brusven and Scoggin 1969; Piorkowski 1997; Minakawa 1997—caddisfly larvae often found on salmon carcasses, sometimes at very high densities. Chaloner et al. 2004—biomass of chironomids was higher in reaches with salmon spawners, while biomass of mayflies was significantly higher in reaches without spawners. Elliott and Bartoo 1981; Piorkowski 1995; Minakawa 1997; Nicola 1968—chironomids and stoneflies feed on carcass flesh and eggs. Minakawa 1997—from late spring to early autumn, invertebrate density and biomass are greater in streams with coho spawners than inaccessible streams. Piorkowski 1995; Minakawa 1997—insects feeding on carcasses invade gill cavity and mouth, moving to all external surfaces as the carcass decomposes. Some insects ingest both the microbes covering the carcass and the flesh. Wipfli et al. 1998—total macroinvertebrate density increased in carcass-enriched areas. Yanai and Kochi 2005—20% of salmon-derived N taken up by shredder invertebrates. Zhang et al. 2003—detrital consumers shifted diet from alder leaves to salmon carcasses.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 7–3] **Direct link** between spawning salmon and water chemistry (nutrients concentrations).	Mathisen et al. 1988 as cited in Naiman et al. 2002 Mitchell and Lamberti 2005 Yanai and Kochi 2005 Chaloner et al. 2004 Johnston et al. 2004		Stream discharge and nutrient inputs from non-salmon sources (e.g., agricultural activities, N-fixing plants, ambient levels) will affect observed concentrations.		Indicators of water quality (N and P concentrations or variables that are strongly related to changes in these water quality criteria). Measure of the ambient conditions of nutrient concentrations in a watershed.	Mathisen et al. 1988—decomposition of carcasses contributes large quantities of dissolved matter to streams. Mitchell and Lamberti 2005—salmon increase concentrations of dissolved nutrients—ammonium and soluble reactive phosphorus increased in the presence of salmon and distance downstream in a salmon reach, nitrate and dissolved organic carbon concentrations varied with discharge. Yanai and Kochi 2005—salmon additions in manipulated streams increased ammonium concentrations.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 7–4] **Indirect link** relating salmon to water quality nutrients and chemical sorption onto the epilithic organic matter film (biofilm) encrusting streambed and hyporheic surfaces.	Edwards 1998; Schuldt and Hershey 1995 as cited in Naiman et al. 2002 Mitchell and Lamberti 2005 Wipfli et al. 1998 Bilby et al. 1996 Chaloner et al. 2002	Mitchell and Lamberti 2005		Extent to which such processes contribute to retention of MD-nutrients is relatively unknown.		Bilby et al. 1996—this process was the most important uptake mechanism for material released by coho salmon carcasses during Nov and Dec in W WA streams. Bilby et al. 1996; Edwards 1998—long-term storage of MD-nutrients in streams regulated by nutrient uptake in epilithic organic matter layer that encrusts the streambed and hyporheic surfaces. Chaloner et al. 2002—incorporation of MD nutrients into stream food webs requires uptake by biofilm. Mitchell and Lamberti 2005—no pattern in epilithon response in natural multi-stream comparison with salmon; increased epilithon standing stock in presence of salmon in artificial streams. Schult and Hershey 1995—addition of Chinook salmon carcasses increased chlorophyll a in epilithic organic layer. Wipfli et al. 1998—ash-free dry mass increased in carcass enriched reaches, no detectable differences in artificial streams.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 7–5] **Indirect link** relating salmon to water quality and uptake of inorganic nutrients by stream autotrophs (e.g., periphyton, algae, vascular plants).	Johnston et al. 1997; Richey et al 1975; Schuldt and Hershey 1995; as cited in Naiman et al. 2002 Yanai and Kochi 2005 Hicks et al. 2005 Johnston et al. 2004	Rand et al. 1992 as cited in Naiman et al. 2002 Ambrose et al. 2004	Low water temperatures and light levels, plus high stream discharge reduce the effectiveness of biological uptake processes. Biological processes dominate during warmer and brighter months (late summer and early fall). Background nutrient levels.			Ambrose et al. 2004—unable to detect an effect of experimental carcass additions on periphyton. Rand et al. 1992—carcasses have little effect on primary production in nutrient-rich streams. Richey et al. 1975—kokanee salmon carcasses stimulated algal production. Schult and Hershey 1995—autotrophic (and heterotrophic) organisms primarily responsible for uptake of dissolved organic matter released by decomposing carcasses in early autumn. Yanai and Kochi 2005—salmon treated streams increased chlorophyll concentrations in epilithic algae
[Fig 7–6] **Indirect link** as aquatic invertebrates assimilate organic matter film (containing MD nutrients) encrusting streambed and hyporheic surfaces.	Schuldt and Hershey 1995 as cited in Naiman et al. 2002 Naiman et al. 2002					Naiman et al. 2002—fragmentation of MD nutrients in streambed layer by invertebrates may enable transport of nutrients to surface waters. Schult and Hershey 1995—heterotrophic organisms responsible for uptake of dissolved organic matter released by decomposing carcasses that has accumulated on the streambed
[Fig 7–A] **Indirect link** relating delivery of MD-nutrients to streams from terrestrial environment. Spawners contribute MD-nutrients to riparian vegetation which is then returned to stream by terrestrial inputs—litterfall, large woody debris, throughfall, and groundwater sources.	Naiman et al. 2002 See additional evidence indicating transfers of MD-nutrients to terrestrial environment in [Fig 4–9]					

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 7–D] **Indirect link** between spawners, smolt production, and export of MD-nutrients. Relatively small proportion of MD-nutrients exported by smolts migrating from streams to the ocean. Nonlinear relationship between nutrient imports by adults and exports by smolts—smolts export proportionally more P as spawners decrease.	Scheuerell et al. 2005		Other habitat factors that control smolt survival.			Scheuerell et al. 2005—estimated that P imports from Chinook spawners over last 40 years are <2% of historical levels. In 12% of years, smolts exported more P than adults imported resulting in a net loss of P from freshwater ecosystem.

Figures 1 and 8: Salmon-Nutrient Links to Terrestrial Vegetation

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3] **Indirect link** between **spawners** and **carcasses** and riparian/terrestrial vegetation. Helfield and Naiman (2001, cited in Schindler et al. 2003) suggest that tree growth is at least partially dependent on healthy salmon populations. Salmon make a measurable contribution to the nutrient capital of riparian ecosystems (Naiman et al. 2002). MD-nitrogen in SE AK can increase the growth rate of Sitka spruce nearly threefold (Naiman et al. 2002). Mean overstory stem density is 100% higher, driven by a 5-fold difference in large-diameter willows (Bartz and Naiman 2005). $\delta^{15}N$ levels in the wood of trees adjacent to streams is directly proportional to salmon numbers [Reimchen 2001). The salmon signature can occur 800m into forests where grizzly bears are common (Reimchen 2001, referring to work by Hilderbrand but not cited explicitly). Importance: three of the most important functions of the riparian forest are related to microclimate, biodiversity, and biogeochemical cycles (Chapter 12 of Naiman and Bilby, 1998). While N fixation by alder may reduce the importance of MDN inputs to riparian conifers, MDN inputs may in turn reduce the proportional abundance of alder in the riparian forest (Helfield and Naiman 2002).	Reimchen 1994, Hilderbrand et al. 1999; Helfield and Naiman 2006, cited in Winder at al. 2005 Gende et al. 2002 Bibly et al. 1996, Hilderbrand et al. 199a, cited in Gende et al. 2002 Schindler et al. 2003 Naiman et al. 2002 Helfield and Naiman 2001, 2002 Naiman et al. 2002 Bartz and Naiman 2005 Reimchen 2001 Chapter 12 of Naiman and Bilby, 1998 Ben-David et al. 1998 Bilby et al. 2003 Drake, Naiman and Helfield 2002 Gresh, Lichatowich and Schoonmaker	Foliar [N] and [P] not enhanced; perhaps salmon-borne nutrients enhance foliar growth, diluting increases in [ ] with added biomass (Bartz and Naiman 2005). No clear evidence for coho, which spawn at lower densities (Bilby et al. 2003). Alder and willow showed no MD-N enrichment (Hicks et al 2005), perhaps for reasons described elsewhere in this table re: alder and spawning density (coho)	Tracking the fate of salmon biomass within ecosystems is difficult because of uncontrolled and poorly quantified confounding factors (Gende et al. 2002). The extent of upslope distribution of MD-nitrogen varies by site and plant species and is influenced by the presence of piscivorous predators (Ben-David et al. 1998, cited in Naiman et al. 2002). Foliar $\delta^{15}N$ may depend on variables other than salmon. Covariates: salmon density in the stream, abundance of bears, plant species, and distance from the stream (Reimchen 2001). Bilby et al. (2003) suggest the link depends on the type of salmon (a proxy for spawning density). They found evidence at a chum spawning creek (chum typically spawn in dense aggregations) but not at a coho spawning creek (coho spawn at lower densities). The point at which nutrient limitation is overcome; large-scale climatic events; regional catch; Pacific Decadal Oscillation; lagging relationship between escapement and tree growth, which varies among sites (Drake, Naiman and Helfield 2002). Foliar $\delta^{15}N$ values might be influenced by factors other than MD-N inputs, such as rooting depth and soil N pools (Schulze	The influence of salmon-derived nutrient inputs on biodiversity is largely unknown (Gende et al. 2002). Can the amount or [ ] of MD-nitrogen in individual tree rings be used to reliably estimate the # of adult salmon returning to spawn in the year the ring was formed? Is tree growth related to the # of fish spawning in the previous year, or is the growth related to the accumulation of N from several previous years? (Naiman et al. 2002)—*Reimchen (2001) found that the peaks in salmon can take 1–3 years to show up in tree rings.* It addition to N and P, salmon carry high concentrations of many biologically important elements, and the ecological significance of these are poorly understood at best (Naiman et al. 2002). The temporal scale over which MD-N enrichment occurs is at this point unknown (Helfield and Naiman 2001). Marine N subsidies appear to be less important to riparian ecosystems where alder are present, but further research is needed to fully characterize the effects of AFN and MD-N on microbial dynamics, N availability and nutrient limitation in riparian soils (Helfield and Naiman 2002).	Estimates of the relationship between escapement (# of spawners) and basin-specific intrinsic factors and productivity (Gende et al. 2002) Long-term, whole-system manipulations are necessary to quantify dose-response relationships and to avoid experimental design flaws in current approaches (Gende et al. 2002) Published research is largely descriptive, not experimental. Long-term ecosystem-scale studies are needed to understand the implications for fishery management and ecosystem resilience in the face of environmental change (Schindler et al. 2003). Growth of Sitka spruce (other species too?) in Pacific coastal rainforest (dendochronology) (Drake, Naiman and Helfield 2002). Mean annual basal area growth within 25m of a spawning stream; or annual growth per unit forest area (m2.ha^{-1}.yr^{-1}) (Helfield and Naiman 2001). Foliar N content and $\delta^{15}N$ of Sitka spruce, devil's club and fern at spawning sites relative to reference sites (Helfield and Naiman 2001); $\delta^{15}N$ in spruce, willow, poplar (Helfield and Naiman 2002); in mosses and liverworts (Wilkinson, Hocking and Reimchen 2005); in humus soil, riparian vegetation *(Tsuga heterophylla, Vaccinium parvifolium, Rubus spectabilis*), and riparian insects including herbivorous and carnivorous *Carabidae* (Reimchen et al. 2002). Not alder which derives most of its N through fixation of atmospheric N2, and would therefore be less likely to sequester MD-N inputs.	Salmon may affect riparian ecosystems in SE and SW AK differently. In SE AK temperate rain forests, salmon-borne nutrients are believed to accelerate the production of LWD, forming a central link in the feedback between salmon and vegetation (Naiman et al. 2002b). In SW AK boreal forests, the feedback is more likely to occur through allochthonous inputs of nutrient-rich willow stems and litter to streams. (Bartz and Naiman 2005) Our analysis of the input of N from salmon carcasses in central Idaho to riparian conifers represents a significant step forward in quantifying the spatial subsidy of terrestrial ecosystems from marine sources. This information will be essential in setting ecologically defensible salmon recovery goals (Peery et al. 2003) for sites that have had severe long term declines in salmon populations. The analysis of δ15N levels in terrestrial components, such as foliage from long-lived conifer species, allows for an integration of salmon inputs across several decades or centuries. Based on our results that conifer forests integrate long-term salmon nutrient inputs and that this signal persists for a long period of time, it may be possible to monitor cascading impacts of salmon extirpation by assessing δ15N levels of riparian conifer foliage. From Koyama, Kavanagh and Robinson 2005.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
	2000 Koyama, Kavanagh and Robinson 2005 Mathewson, Hocking and Reimchen 2003 Wilkinson, Hocking and Reimchen 2005 Reimchen et al. 2002		et al. 1994; Handley and Scrimgeour 1997), and isotopic fractionation associated with microbial N processing in soils (Nadelhoffer and Fry 1994), all of which vary spatially within any given watershed according to differences in slope, elevation and soil texture.. From Helfield and Naiman 2002. MD-N uptake by white spruce appears to be influenced by the presence of alder (Helfield and Naiman 2002). Alder and salmon abundance may be inversely correlated, but both may be controlled by broader geomorphic factors (e.g., slope, valley shape) rather than by each other (Helfield and Naiman 2002). It is important to consider topographic variation when interpreting foliar δ15N patterns, since several N processes can vary topographically. Variations in N processes in riparian areas can result in increasing foliar δ15N patterns in riparian foliage relative to upslope foliage, making it difficult to distinguish salmon effects (Koyama, Kavanagh and Robinson 2005).			

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–1] **Direct link** between MD-nutrients in **spawners** and **carcasses** and wildlife species that consume salmon. More than 90% of the N in the diet of coastal brown bears in Alaska is from salmon (Hilderbrand et al. 1996, cited in Naiman et al. 2002) Brown bears and bald eagles utilize MD-nutrients immediately before hibernation or making long migrations; and river otters, mink, gulls and other animals utilize these nutrients just before a long winter with limited food resources (Naiman et al. 2002). The timing of lactation in mink has been shown to vary regionally along the north Pacific Coast of NA, coinciding with the arrival of salmon (Ben-David and Schell 1997, cited in Naiman et al. 2002). The indirect effects of declining salmon populations on these and other animals are suspected to be profound in terms of survivorship, fecundity, ability to compete, and other life history requirements (Naiman et al. 2002).	Hilderbrand et al. 1996, cited in Naiman et al. 2002 Naiman et al. 2002 Reimchen 2001 Darimont and Reimchen 2002		Though 90% of the N in bear diets in AK come from salmon, this may not represent the proportion of the diet composed of salmon because some of the MD-nitrogen is likely obtained from riparian plants that have incorporated MD-nutrients (Naiman et al. 2002).	Unfortunately, there are few data to document indirect effects on the vitality of animal populations that rely on MD-nutrients for nutrition (Naiman et al. 2002). Finer reconstruction of trophic processes in wolves and other mammals would benefit from improved information on the timing of hair growth and resource availability (Darimont and Reimchen 2002).	With a few notable exceptions, comparisons of stable isotope values between or among metabolically inert tissue portions grown during different periods show great promise but are as of yet inadequately exploited in dietary reconstructions (Darimont and Reimchen 2002).	

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–1,4] **Indirect link** between **spawners** and **carcasses** and riparian/terrestrial ecosystems via wildlife species that consume salmon, and via Indigenous Peoples who consume(d) and trade(d) salmon. Bears foraging at streams in BC move 58–90% of all salmon biomass to land, sometimes hundreds of meters from the stream; and further distribute the minerals and nutrients in the form of urine and feces as they move throughout the riparian and upland forests. In the PNW, bears serve as important vectors of salmon-derived nutrients into riparian systems. 15.5–17.8% of the total N in spruce foliage. within 500 m of the stream was derived from salmon. Of that, bears had distributed 83–84%. Thus, brown bears can be an important vector of salmon-derived N into riparian ecosystems (Hilderbrand et al. 1999–Oecologia).	Cederholm et al. 2000 Reimchen 2000, Hilderbrand et al. 1999a, Helfield and Naiman 2001 Gende et al. 2002 Schindler et al. 2003 Bilby et al. 1996, cited in Schindler et al. 2002 Reimchen 2001 Ben-David et al. 1998 Hilderbrand et al. 1999 (Oecologia 121:546–550) Quinn et al. 2003		All plant species collected from latrine sites, except for alder, had significantly higher values of ^{15}N than plants collected from non-latrine sites, reflecting the incorporation of MD-nitrogen from otter excretions. Because alder derives most of its N from the atmosphere via N fixation (Bormann and Gordon 1984), we expected that the fertilization by otters would have no effect on the ^{15}N in that species (Ben-David et al. 1998). The effects of bears as a vector of salmon-derived N into riparian ecosystems are highly variable spatially and a function of bear density (Hilderbrand et al. 1999–Oecologia).	Range of historic nutrient loadings to systems where salmon are now excluded (e.g., Canadian Columbia River); proportion attributable to salmon. Basin nutrient budgets.		The distinction between the two dispersal pathways is particularly important with reference to the techniques commonly used to infer the importance of salmon-derived inputs at population and ecosystem levels (Gende et al 2002).
[Fig 1–3, 8–2,3,5] **Indirect link** between salmon and vegetation via scavengers consuming carcasses or salmon first killed by vertebrate predators (and dragged from the stream)	Ben-David et al. 1998, Hilderbrand et al. 1999, Reimchen 2000, cited in Schindler et al. 2003 Meehan, Seminet-Reneau and Quinn 2005					

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–4,5] **Indirect link** between **spawners** and **carcasses** and riparian/terrestrial ecosystems via "recycling": decomposition, leaching and excretion (feces, urine).	Gende et al. 2002 Schindler et al. 2003 Hilderbrand et al. 1999, cited in Naiman et al 2002 Ben-David et al. 1998		See above, regarding alder.	The use of stable isotopes to infer the magnitude of transfers within recycling processes, although increasingly used, is poorly documented and highly speculative compared with the consumption pathway. By extension, it should not be assumed that the importance of salmon biomass as food is directly correlated with the importance of inorganic nutrients to bottom-up pathways (Gende et al. 2002).		
[Fig 1–3, 8–5] **Indirect link** between salmon (spawners, carcasses) and terrestrial vegetation via flying aquatic insects from salmon streams/lakes into riparian forests	TB Francis pers obs, cited in Schindler et al. 2003					
[Fig 1–3, 8–6] **Direct link** between salmon (spawners, carcasses) and terrestrial vegetation through dispersal via floods (and subsequent decay).	Cederholm et al. 1989, cited in Schindler et al. 2003 and in Naiman et al. 2002.		Current research suggests that this may not e a major pathway for MD-nutrient transport (Naiman et al. 2002).	The importance of these processes has not been evaluated at sites with extensive hyporheic zones or where spawning occurs at times when flood flows are common. Under optimal conditions, these pathways may play a more significant role in lateral distribution (Naiman et al. 2002).		
[Fig 1–3, 8–7] **Direct link** between salmon (spawners, carcasses) and terrestrial vegetation through dispersal via subsurface water flows into riparian zones (hyporheic flows).	Clinton et al. 2002, cited in Schindler et al. 2003 Naiman et al. 2002		The few data collected to date suggest that this may not e a primary pathway except during peak spawning runs (Naiman et al. 2002).			

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–8] **Indirect link** between salmon and riparian plants via direct root transfer, which moves MD-nutrients farther into riparian/terrestrial forests.	Naiman et al. 2002			Upslope transfer of MD-nutrients between plants has never been measured (Naiman et al. 2002).		
[Fig 1–3, 8–8] **Indirect link** between salmon and riparian plants via litterfall, which moves MD-nutrients farther into riparian/terrestrial forests.	Naiman et al. 2002					
[Fig 1–3, 8–9] **Indirect link** between increased growth of riparian vegetation and characteristics of adjacent streams.	Gende et al. 2002 Helfield and Naiman 2001, cited in Gende et al. 2002 Helfield and Naiman 2001, 2002					

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–10] **Indirect link** between salmon and ecosystem function, via changes in riparian and terrestrial vegetation. That willows drive the difference in overstory density may have further ecosystem-scale implications. Willows are a preferred source of food for many mammals in northern regions (Viereck and Little 1986). Feltleaf willow, in particular, is the favoured fare of moose, snowshoe hare and willow ptarmigan during winter (West and Meng 1966, Wolff 1980). Given that the overstory willows in this study consist primarily of feltleaf willow, the upstream–downstream difference in density may have broader ecological consequences. From Bartz and Naiman 2005. Salmon nutrient subsidies to terrestrial habitats may result in shifts in invertebrate community structure, with subsequent implications for higher vertebrate consumers, particularly the passerines (Hocking and Reimchen 2002).	Bartz and Naiman 2005 Viereck and Little 1986, West and Meng 1966, Wolff 1980, cited in Bartz and Naiman 2005 Hocking and Reimchen 2002 Mathewson, Hocking and Reimchen 2003					
[Fig 1–3, 8–11] **Indirect link** between salmon and riparian soils: significant soil ^{15}N enrichment at sites with high salmon carcass density and piscivore activity (Bartz and Naiman 2005). Direct relationship between soil ^{15}N and salmon density (Reimchen 2001).	Bartz and Naiman 2005 Reimchen 2001 Reimchen et al. 2002	Surface mineral soil [N] (Bartz and Naiman 2005), thought the results might indicate vegetative uptake.		Salmon may not be the sole source of ^{15}N enrichment. Microbial processes also concentrate ^{15}N by discriminating against N compounds containing the heavier isotope (Nadelhoffer and Fry 1994, cited in Bartz and Naiman 2005).		

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–3, 8–12] Amplification of ^{15}N at multiple trophic levels, including herbivores, omnivores, carnivores and detritivores, extending not from direct consumption of carcasses but from **indirect** food web effects.	Reimchen 2001					

Figures 1 and 9: Salmon-Terrestrial Food Web Links

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–4, 9–1] **Direct link** between **spawners** and vertebrate predators. Osprey, bald eagle, black bear, grizzly bear, and northern river otter all have a "strong, consistent relationship" to salmon, meaning salmon play (or historically played) an important role in species distribution, viability, abundance and/or population status (Cederholm et al. 2000). (In all, 16 wildlife species consume spawning salmon.) The carrying capacity of bears increases where salmon are available, with populations up to 80 times denser in coastal areas where salmon are abundant compared with interior areas (Schindler at al. 2003). The demography of grizzly bear populations at salmon streams changed dramatically in association with observed levels of salmon availability (Boulanger et al. 2004). Availability of meat, particularly salmon, greatly influences habitat quality for brown bears at both the individual level and the population level (Hilderbrand et al. 1999–CJZ). Among females coastal, salmon-eating bears were the largest and interior, vegetarian bears the smallest.	Johnson et al. In prep., as cited in Cederholm et al. 2000 (more general spawner-wildlife food link: Shuman 1950, cited in Gende et l. 2002) Hansen 1987, Ben-David 1997,Hilderbrand et al. 1999c, cited in Gende et al. 2002 Schindler et al. 2003 Ben-David et al. 1998 Miller et al. 1997, Hilderbrand et al. 1999b, cited in Gende et al. 2002 (and in Schindler et al. 2003) Boulanger et al. 2004 Darimont, Reimchen and Paquet 2003 Hilderbrand et al. 1999 (Can. J. Zool. 77: 132–138) Hilderbrand et al. 1999 (Oecologia 121:546–550) Klinka and Reimchen 2002 Quinn et al. 2003 Wilson and Halupka 1995		Other factors affecting abundance, distribution, viability and population status, including availability and quality of other food sources, changes in habitat quality and quantity, disturbance, mortality (predation, disease, hunting, etc.).	The magnitude and extent of the impact on these species from changes in the abundance of spawners. The relationship between gray wolves and salmon remains poorly understood (Darimont, Reimchen and Paquet 2003).	Population trends for these species where their ranges include habitat with salmon spawning streams. Data required by the Pradel model for providing estimates of population trend and valuable information about trends in population demography (this model and DNA sampling were used by Boulanger et al. 2004. They used covariates to explore how changes in environmental conditions influence grizzly bear population demography and population trend.	There is a Direct link between all 5 life stages and 138 species of wildlife, through a strong consistent relationship; recurrent relationship, indirect relationship, or rare relationship. Those terrestrial or riparian species with a "strong and consistent relationship" are most relevant here.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–4, 9–1] **Direct link** between **carcasses** and vertebrate predators. Bald eagle, black bear, grizzly bear, and northern river otter all have a "strong, consistent relationship" to salmon, meaning that salmon play (or historically played) an important role in species distribution, viability, abundance and/or population status (Cederholm et al. 2000). (In all, 71 wildlife species are direct consumers of carcasses, 22 are consumers of carcass-derived insects, and 10 are consumers of both)	Johnson et al. In prep., as cited in Cederholm et al. 2000 Ehrlich et al. 1988, as cited in Kelsey and West 1998 (Ch. 10 in Naiman & Bilby 1998) Gresh, Lichatowich and Schoonmaker 2000		Other factors affecting abundance, distribution, viability and population status, including availability and quality of other food sources, changes in habitat quality and quantity, disturbance, mortality (predation, disease, hunting, etc.).	The magnitude and extent of the impact on these species from changes in the abundance carcasses	See above	There is a Direct link between all 5 life stages and 138 species of wildlife, through a strong consistent relationship; recurrent relationship, indirect relationship, or rare relationship. Those terrestrial or riparian species with a "strong and consistent relationship" are most relevant here.
[Fig 1–4, 9–2,3] **Direct link** between salmon and scavengers (both vertebrate and invertebrate)	Schindler et al. 2003 Wilson and Halupka 1995			Population trends for these species where their ranges include habitat with salmon spawning streams		
[Fig 1–4, 9–4,5] **Indirect link** between **spawners** and growth of scavengers (including aquatic macroinvertebrates) via bears and other mammals and birds that kill and consume salmon, by altering the temporal availability, accessibility and quality of an important food resource. Salmon killed by predators (compared with carcasses of senescent individuals) provide food with higher energetic content to scavengers, earlier in the run, and also open carcasses which improves accessibility of consumable tissue.	Winder et al. 2005 Jauquet et al. 2003, and Hendry and Berg 1999, cited in Winder et al. 2005 Meehan, Seminet-Reneau and Quinn 2005		Salmon density (In sites with low salmon densities and high bear activity, it is likely that bears reduce salmon resource subsidies available to macroinvertebrates [and other scavengers], especially if bears consume high proportions of salmon and carry them into the riparian zone), quality and quantity of other food sources available to scavengers.		There are too many confounding factors to develop practical and meaningful indicators for this link.	Bear foraging behaviour can have a strong impact on the mode of death of migrating salmon. Quinn and Buck 2000, and Gende et al. 2001, cited in Winder et al. 2005 found that nearly all salmon arriving early on the spawning grounds were killed by bears, and at one site were available to scavengers about a week before carcasses of senescent individuals were observed. This link demonstrates the importance of distinguishing between types of carcasses.

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–4, 9–3,6] **Indirect link** between salmon and insectivores via invertebrate scavengers. In SE AK, the riparian forests bordering salmon streams supported, on average, higher densities, but not diversity, of forest passerines compared to non-salmon streams (Gende and Wilson 2001).	Gende and Willson 2001		On an annual basis, the number of flies may be more limited by temperature extremes than number of spawners (Schindler et al. 2003) Amount of deciduous vegetation (Gende and Wilson 2001)	The # of invertebrates present in the fall undoubtedly influences the number of invertebrates emerging in the spring, but the magnitude of the effect is unknown (Gende and Wilson 2001). The absolute and relative importance of various pathways of nutrient flow up the food chain remain to be examined; e.g., herbivorous insects often target foliage that is growing rapidly or has elevated levels of nitrogen (Feeny 1970, Price 1991), potentially leading to higher abundances on foliage with MD-nitrogen subsidies (Gende and Wilson 2001).	Densities of forest passerines. Studies are needed to separate clearly the effects of salmon and deciduous vegetation. Linkages between spawning fish and passerines could be confirmed using stable isotope analysis to detect marine signatures of invertebrates consumed by riparian passerines. Species-specific studies of diet and foraging behaviour will also help interpret why some species (e.g., Pacific-slope Flycatcher) exhibit a greater numerical response on salmon streams than other species (e.g., Varied Thrush) (Gende and Wilson 2001).	
[Fig 1–4, 9–7] **Indirect link** between bears (and bear density, movement) and coastal forest plant species for whom bears are important agents of seed dispersal	Willson 1993, cited in Gende et al. 2002			Consequences on seed dispersal patters from lower bear densities resulting from loss of salmon in the system	"	
[Fig 1–4, 9–7] **Indirect link** between vertebrate wildlife species with a "strong, consistent relationship" to salmon and an array of key ecological functions (trophic relations, primary consumption, organismal relations, wood relations). Most of the 5 live stages provide for a unique set of wildlife species and their ecological function; therefore to manage for a full set of ecological functions, one should focus on providing all life stages of salmon.	Cederholm et al. 2000		Many other factors that affect these wildlife species; and many other factors that affect these ecological functions	The magnitude and extent of the impact on these species from changes in the abundance of salmon (particularly spawners and carcasses); the nature, magnitude and extent of impact on these ecological functions from changes in the abundance of these species	"	

Link and management relevance	Evidence for	Evidence against	Covariates or confounding factors	Critical uncertainties	Data requirements	Details of study / other comments
[Fig 1–4, 9–8,9] **Indirect link** between species that prey on salmon and other species: predation by secondary consumers (species that prey on species that eat salmon), competition, parasitism, other aggressive interactions. Loss or severe depletion of anadromous fish stocks could have major effects on population biology (i.e., age class, longevity, dispersal ability) of many wildlife species, and thus, on the overall health and functioning of natural communities over the majority of the region.	Cederholm et al. 2000 Gende et al. 2002		Many other factors that affect population biology	The magnitude and extent of the impact on these species from changes in the abundance of salmon, and changes in the abundance of the primary salmon consumers	There are too many confounding factors to develop practical and meaningful indicators for this link.	

APPENDIX B: REFERENCES CITED IN APPENDIX A

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APPENDIX C: INDICATOR TABLES

Part 1: Indicator Description

Type I Indicators

Management questions	Indicator theme	Candidate indicator(s)	Related ecosystem, conceptual diagram, and linkage number	Type of monitoring
	(i.e., What should managers measure / monitor?)	*(i.e., Which specific data should be collected or indicators should be quantified?)*		
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	*sea surface temperature (SST) *Pacific Decadal Oscillation (PDO) *El Nino-Southern Oscillation (ENSO) *Coastal Upwelling Indices (CUI) *Oyster Condition Indicator (OCI)	all ecosystems Figure 1–1	Baseline / validation monitoring
	harvest rate	*First Nations catch monitoring *commercial catch estimates *recreational harvest	all ecosystems Figure 1–1	Baseline monitoring
	implementation uncertainty	*difference between target and realized harvest rates	all ecosystems Figure 1–1	Implementation monitoring
	stock abundance	*abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) *escapement estimates (e.g., NuSEDs)	all ecosystems Figure 1–1	Baseline monitoring
	enroute mortality (1)	*discharge	all ecosystems Figure 1–1	Validation monitoring
	enroute mortality (2)	*estimates of enroute mortality *water temperature *disease incidence / virulence	all ecosystems Figure 1–1	Validation monitoring
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter, harbour seals, sea lions	all ecosystems Figure 1–4	Baseline / validation monitoring

APPENDIX C: INDICATOR TABLES

Part 1: Indicator Description

Type I Indicators

Management questions	Indicator theme	Candidate indicator(s)	Related ecosystem, conceptual diagram, and linkage number	Type of monitoring
	(i.e., What should managers measure / monitor?)	*(i.e., Which specific data should be collected or indicators should be quantified?)*		
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	•sea surface temperature (SST) •Pacific Decadal Oscillation (PDO) •El Nino-Southern Oscillation (ENSO) •Coastal Upwelling Indices (CUI) •Oyster Condition Indicator (OCI)	all ecosystems Figure 1–1	Baseline / validation monitoring
	harvest rate	•First Nations catch monitoring •commercial catch estimates •recreational harvest	all ecosystems Figure 1–1	Baseline monitoring
	implementation uncertainty	•difference between target and realized harvest rates	all ecosystems Figure 1–1	Implementation monitoring
	stock abundance	•abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) •escapement estimates (e.g., NuSEDs)	all ecosystems Figure 1–1	Baseline monitoring
	enroute mortality (1)	•discharge	all ecosystems Figure 1–1	Validation monitoring
	enroute mortality (2)	•estimates of enroute mortality •water temperature •disease incidence / virulence	all ecosystems Figure 1–1	Validation monitoring
	abundance of predators	•abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter, harbour seals, sea lions	all ecosystems Figure 1–4	Baseline / validation monitoring

Type II Indicators

Management questions	Indicator theme	Candidate indicator(s)	Related ecosystem, conceptual diagram, and linkage number	Type of monitoring
	(i.e., What should managers measure / monitor?)	*(i.e., Which specific data should be collected or indicators should be quantified?)*		
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values (see Figure 4, lines A and B)	human disturbance—forestry, agriculture	•area of agricultural activity •watershed area with forest harvesting	lakes Figure 6–A streams Figure 7–B, 3–C terrestrial vegetation Figure 8–11	Baseline / validation monitoring
	human disturbance—effluent sources	•location of point source discharges	lakes Figure 6–A streams Figure 7–B, 3–C terrestrial vegetation Figure 8–11	Baseline / validation monitoring
	restoration activities	•lake fertilization •stream fertilization •carcass enhancement •forest fertilization	lakes Figure 6–A streams Figure 7–B, 3–C terrestrial vegetation Figure 8–11	Baseline / validation monitoring
	watershed / ecosystem characteristics	•elevation •BEC •stream geomorphology •groundwater •EAU BC	streams streams Figure 7–3, 7–B, 7–C	Baseline / validation monitoring
	hydrology	•discharge •lake flushing rate •annual precipitation •watershed drainage area	lakes Figure 6–A streams Figure 7–3, 7–B, 7–C	Baseline / validation monitoring
	vegetation cover	•BEC •length of stream with riparian harvesting •riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)	riparian / terrestrial ecosystem	Validation monitoring
	bedrock geology	•classification of bedrock geology	lakes Figure 6–A streams Figure 7–B, 7–C	Validation monitoring
	microbial processing	uncertain	all ecosystems	Validation monitoring

Management questions	Indicator theme	Candidate Indicator(s)	Related ecosystem, conceptual diagram, and linkage number	Type of monitoring
	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) *acidity (pH), alkalinity *water temperature *Total dissolved solids (TDS)	lakes Figure 6–3 streams Figure 6–3	Validation monitoring
	spawner abundance (1)	*escapement estimates (e.g., NuSEDs)	primary driver in all ecosystems Figure 1–3, 1–4	Baseline monitoring
	spawner abundance (2)	*historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	primary driver in all ecosystems Figure 1–3, 1–4	Baseline monitoring
	salmon distribution	*fish distribution mapping	primary driver in all ecosystems Figure 1–3, 1–4	Baseline monitoring
	distribution of predators	*distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	riparian/terrestrial ecosystem Figure 8–1, 9–1	Baseline / validation monitoring
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	riparian/terrestrial ecosystem Figure 8–1, 9–1	Baseline / validation monitoring

Type III Indicators

Management questions	Indicator theme	Candidate indicator(s)	Related ecosystem, conceptual diagram, and linkage number	Type of monitoring
	(i.e., What should managers measure / monitor?)	*(i.e., Which specific data should be collected or indicators should be quantified?)*		
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems? (see Figure 5, lines A, B, C, and D)	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)	lakes Figure 6–3 streams Figure 7–3	Effectiveness / baseline monitoring
	primary productivity	*algal (blue-green algae), macrophyte, and/or phytoplankton biomass *chlorophyll a *diatom biomass (or community diversity)	lakes Figure 6–4 streams Figure 7–5	Effectiveness / baseline monitoring
	secondary productivity	*zooplankton biomass (or community diversity)	lakes Figure 6–2, 6–5	Effectiveness / baseline monitoring
	macroinvertebrate production	*index of biological integrity (IBI) *invertebrate biomass (or community diversity)	streams Figure 7–2, 7–6	Effectiveness / baseline monitoring
	juvenile fish production (other species and/or salmon life stages)	*salmon smolt abundance *juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) *juvenile weight	lakes Figure 6–1, 6–6 streams Figure 7–1, 7–8	Effectiveness / baseline monitoring
	timing of stock migration	*migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	all ecosystems Figure 1–1	Baseline monitoring
	sediment layer	*analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)	lakes Figure 6–7	Effectiveness / baseline monitoring
	fine sediment layer	uncertain	streams Figure 7–4	Effectiveness / baseline monitoring
	vegetation	*foliar N and δ15N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) *tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m2/ha/yr])	riparian/terrestrial ecosystem Figure 8	Effectiveness / baseline / validation monitoring
	riparian insects	* δ15N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	riparian/terrestrial ecosystem Figure 8–2,3	Effectiveness / baseline / validation monitoring

Part 2: Evaluation Criteria

Type I Indicators

Management questions	**Indicator theme**	**Candidate indicator(s)**	**Technical considerations**					**Management relevance**		**Ecological relevance**	
			data availability	**spatial extent**	**temporal frequency**	**additional cost**	**accuracy and precision**	**related management question**	**relative importance**	**strength of cause-effect link**	**indicator of broader ecosystem changes**
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	•sea surface temperature (SST) •Pacific Decadal Oscillation (PDO) •El Nino-Southern Oscillation (ENSO) •Coastal Upwelling Indices (CUI) •Oyster Condition Indicator (OCI)	yes	regional	daily to annual	low	uncertain	I	uncertain	important covariate strong relationship	yes
	harvest rate	•First Nations catch monitoring •commercial catch estimates •recreational harvest	yes	basin / provincial	weekly / annual	low	uncertain	I	high	indirect link strong relationship	no
	implementation uncertainty	•difference between target and realized harvest rates	yes	localized	annual	uncertain	uncertain	I	uncertain	indirect link uncertain	no
	stock abundance	•abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) •escapement estimates (e.g., NuSEDs)	yes	watershed / basin	annual	moderate	low to moderate	I	uncertain	direct link strong relationship	yes
	enroute mortality (1)	•discharge	yes	localized / watershed	daily	moderate	high	I	uncertain	important covariate uncertain	no
	enroute mortality (2)	•estimates of enroute mortality •water temperature •disease incidence / virulence	Uncertain					I	uncertain	important covariate uncertain	no
	abundance of predators	•abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	yes	provincial	mostly annual	low	moderate	I	uncertain	important covariate uncertain	no

Part 2: Evaluation Criteria

Type I Indicators

Management questions	Indicator theme	Candidate indicator(s)	Technical considerations					Management relevance		Ecological relevance	
			data availability	spatial extent	temporal frequency	additional cost	accuracy and precision	related management question	relative importance	strength of cause-effect link	indicator of broader ecosystem changes
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	*sea surface temperature (SST) *Pacific Decadal Oscillation (PDO) *El Nino-Southern Oscillation (ENSO) *Coastal Upwelling Indices (CUI) *Oyster Condition Indicator (OCI)	yes	regional	daily to annual	low	uncertain	I	uncertain	important covariate strong relationship	yes
	harvest rate	*First Nations catch monitoring *commercial catch estimates *recreational harvest	yes	basin / provincial	weekly / annual	low	uncertain	I	high	indirect link strong relationship	no
	implementation uncertainty	*difference between target and realized harvest rates	yes	localized	annual	uncertain	uncertain	I	uncertain	indirect link uncertain	no
	stock abundance	*abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) *escapement estimates (e.g., NuSEDs)	yes	watershed / basin	annual	moderate	low to moderate	I	uncertain	direct link strong relationship	yes
	enroute mortality (1)	*discharge	yes	localized / watershed	daily	moderate	high	I	uncertain	important covariate uncertain	no
	enroute mortality (2)	*estimates of enroute mortality *water temperature *disease incidence / virulence	Uncertain					I	uncertain	important covariate uncertain	no
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	yes	provincial	mostly annual	low	moderate	I	uncertain	important covariate uncertain	no

Type II Indicators

Management questions	Indicator theme	Candidate indicator(s)	Technical considerations					Management relevance		Ecological relevance	
			data availability	spatial extent	temporal frequency	additional cost	accuracy and precision	related management question	relative importance	strength of cause-effect link	indicator of broader ecosystem changes
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values (see Figure 4, lines A and B)	human disturbance—forestry, agriculture	•area of agricultural activity •watershed area with forest harvesting	yes	provincial	decadal	low	low	II	uncertain	important covariate	yes
	human disturbance—effluent sources	•location of point source discharges	yes	localized / watershed	annual	moderate	moderate	II	uncertain	potentially confounding variable	no
	restoration activities	•lake fertilization •stream fertilization •carcass enhancement •forest fertilization	yes	localized	annual	low	low	II	uncertain	important covariate	yes
	watershed / ecosystem characteristics	•elevation •BEC •stream geomorphology •groundwater •EAU BC	yes	watershed	decadal	moderate	moderate	II	uncertain	important covariate	no
	hydrology	•discharge •lake flushing rate •annual precipitation •watershed drainage area	yes	localized / watershed	daily / monthly	low	low	II	uncertain	important covariate	yes
	vegetation cover	•BEC •length of stream with riparian harvesting •riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)	yes	watershed	decadal	low	low	II	uncertain	direct and indirect link, potentially confounding variable strong relationship	yes
	bedrock geology	•classification of bedrock geology	yes	provincial	decadal	low	moderate	II	uncertain	important covariate	uncertain

Management questions	**Indicator theme**	**Candidate indicator(s)**	**Technical considerations**					**Management relevance**		**Ecological relevance**	
			data availability	**spatial extent**	**temporal frequency**	**additional cost**	**accuracy and precision**	**related management question**	**relative importance**	**strength of cause-effect link**	**indicator of broader ecosystem changes**
	microbial processing	uncertain	Uncertain					II	uncertain	potential confounding variable	uncertain
	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) *acidity (pH), alkalinity *water temperature *Total dissolved solids (TDS)	yes	localized / watershed	weekly (Environment Canada Water Quality Monitoring index sites) decadal (BC Lakes Database, FDIS, bedrock geology)	moderate	high	II	uncertain	direct link strong relationship	yes
	spawner abundance (1)	*escapement estimates (e.g., NuSEDs)	yes	watershed	annual	moderate	moderate	II	uncertain	direct link strong relationship	yes
	spawner abundance (2)	*historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	Uncertain					II	uncertain	direct link strong relationship	yes
	salmon distribution	*fish distribution mapping	yes	watershed	decadal	low	low	II	uncertain	direct link strong relationship	yes
	distribution of predators	*distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	yes	provincial	mostly annual	low	moderate	II	uncertain	direct link strong relationship	yes
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	yes	provincial	mostly annual	low	moderate	II	uncertain	direct link strong relationship	yes

Type III Indicators

Management questions	Indicator theme	Candidate indicator(s)	Technical considerations					Management relevance		Ecological relevance	
			data availability	spatial extent	temporal frequency	additional cost	accuracy and precision	related management question	relative importance	strength of cause-effect link	indicator of broader ecosystem changes
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems? (see Figure 5, lines A, B, C, and D)	water quality / chemistry	•N concentration (nitrate, nitrite, ammonia) •P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)	yes	localized	weekly (Environment Canada Water Quality Monitoring—index sites) decadal (BC Lakes Database, FDIS)	moderate	high	III	uncertain	direct link strong relationship	yes
	primary productivity	•algal (blue-green algae), macrophyte, and/or phytoplankton biomass •chlorophyll a •diatom biomass (or community diversity)	Uncertain					III	uncertain	indirect link strong relationship	yes
	secondary productivity	•zooplankton biomass (or community diversity)	Uncertain					III	uncertain	indirect and direct link moderate relationship	yes
	macroinvertebrate production	•index of biological integrity (IBI) •invertebrate biomass (or community diversity)	yes (but limited and sporadic)	localized	annual	low	low	III	uncertain	indirect and direct link moderate relationship	yes
	juvenile fish production (other species and/or salmon life stages)	•salmon smolt abundance •juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) •juvenile weight	uncertain	watershed	annual	high	moderate	III	uncertain	indirect and direct link weak relationship	yes
	timing of stock migration	•migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	yes	basin	daily	high	high	III	uncertain	direct link strong relationship	uncertain

Management questions	Indicator theme	Candidate indicator(s)	Technical considerations					Management relevance		Ecological relevance	
			data availability	spatial extent	temporal frequency	additional cost	accuracy and precision	related management question	relative importance	strength of cause-effect link	indicator of broader ecosystem changes
	sediment layer	*analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)	uncertain					III	uncertain	indirect relationship strong relationship	uncertain
	fine sediment layer	uncertain	uncertain					III	uncertain	indirect relationship uncertain	uncertain
	vegetation	*foliar N and δ15N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) *tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m2/ha/yr])	uncetain	localized	annual, but not long-term (1–3 years)	uncertain	high	III	uncertain	both direct and indirect links, strong relationship (ample evidence)	yes
	riparian insects	* δ15N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	uncertain	localized	snapshot	uncertain	high	III	uncertain	both direct and indirect links, moderate relationship (some evidence)	uncertain

Part 3: Priority, Rationale, Next Stages

Type I Indicators

Management questions	Indicator theme	Candidate indicator(s)	Priority high, moderate, low	General comments general thoughts on why indicator theme is recommended and reason for ranking	Next stages extensive analytical studies, intensive multi-watershed experiments, adaptive management, or none
Type I Indicators— Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	•sea surface temperature (SST) •Pacific Decadal Oscillation (PDO) •El Nino-Southern Oscillation (ENSO) •Coastal Upwelling Indices (CUI) •Oyster Condition Indicator (OCI)	Low	Need to better understand relationships between changes in salmon survival and marine conditions (see Peterman et al. stock-recruitment models).	
	harvest rate	•First Nations catch monitoring •commercial catch estimates •recreational harvest	High	This indicator is the key policy lever that will control escapement and potential influences on terrestrial and freshwater ecosystems. It is critical to discuss escapement goals (and related ecosystem effects) in the context of setting harvest rates (i.e., socio-economic indicators will be key considerations for managers).	extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	implementation uncertainty	•difference between target and realized harvest rates	Medium	Analyses have been initiated, need to complete for more stocks and integrate results into management systems.	
	stock abundance	•abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) •escapement estimates (e.g., NuSEDs)	High	Stock abundance needed for salmon management and to understand implications of changes in spawner abundance on the broader ecosystem.	extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	enroute mortality (1)	•discharge	Low	Need to better understand effects of changes in freshwater conditions on enroute mortality and integrate these factors into salmon management.	
	enroute mortality (2)	•estimates of enroute mortality •water temperature •disease incidence / virulence	Low	Need to better understand effects of changes in freshwater conditions on enroute mortality and integrate these factors into salmon management.	
	abundance of predators	•abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	Low	As detailed by the linkages described in Figure 9, terrestrial salmon predators will also influence spawner abundance. The nature and strength of these linkages on controlling salmon abundance is unclear.	extensive analytical studies, intensive multi-watershed experiments, and adaptive management

Type II Indicators

Management questions	Indicator theme	Candidate indicator(s)	Priority high, moderate, low	General comments general thoughts on why indicator theme is recommended and reason for ranking	Next stages extensive analytical studies, intensive multi-watershed experiments, adaptive management, or none
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values (see Figure 4, lines A and B)	human disturbance—forestry, agriculture	*area of agricultural activity *watershed area with forest harvesting	High	Would provide information on anthropogenic inputs of nutrients.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	human disturbance—effluent sources	*location of point source discharges	High	Would provide information on anthropogenic inputs of nutrients.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	restoration activities	*lake fertilization *stream fertilization *carcass enhancement *forest fertilization	High	Nutrient enhancement programs will affect nutrient loadings into freshwater and terrestrial environments and their related ecosystems.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	watershed / ecosystem characteristics	*elevation *BEC *stream geomorphology *groundwater *EAU BC	Medium	Would help identify those ecosystems (or watersheds) that are most likely to respond positively to changes in salmon abundance, based on ecosystem / watershed features that covary with nutrients changes.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	hydrology	*discharge *lake flushing rate *annual precipitation *watershed drainage area	High	Nutrient concentrations affected by discharge. This indicator theme would help identify those locations that may be most responsive to changes in spawner abundance.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	vegetation cover	*BEC *length of stream with riparian harvesting *riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)	Medium	Vegetation cover affects litterfall inputs of nutrients into streams and nitrogen fixing plants affect terrestrial and freshwater nutrient cycles.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	bedrock geology	*classification of bedrock geology	Medium	Important factor that influences water quality. May be considered as part of EAU BC classifications.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	microbial processing	uncertain	Low	Microbial processes can preferentially fix	extensive analytical studies, intensive multi-watershed experiments, and adaptive management

Management questions	Indicator theme	Candidate Indicator(s)	Priority high, moderate, low	General comments general thoughts on why indicator theme is recommended and reason for ranking	Next stages extensive analytical studies, intensive multi-watershed experiments, adaptive management, or none
	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) *acidity (pH), alkalinity *water temperature *Total dissolved solids (TDS)	High	Will provide information on background sources of nutrient inputs.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	spawner abundance (1)	*escapement estimates (e.g., NuSEDs)	High	The key independent variables of interest driving ecosystem responses.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	spawner abundance (2)	*historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	High	The key independent variables of interest driving ecosystem responses.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	salmon distribution	*fish distribution mapping	High	Use current (and historic) spatial distribution to prioritize those areas where managers should focus their efforts on salmon management.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	distribution of predators	*distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	High	Since these predators (some of which also scavenge) are the first link (and the one for which there is most evidence) in the transfer of salmon through the riparian/terrestrial food web as well as the transfer of marine-derived nutrients to riparian/terrestrial ecosystems, it makes sense to focus management effort in watersheds where these species already occur, or where habitat suitability (capability under current conditions) for these species is high.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	High	Same as above.	Extensive analytical studies, intensive multi-watershed experiments, and adaptive management

Type III Indicators

Management questions	Indicator theme	Candidate indicator(s)	Priority high, moderate, low	General comments general thoughts on why indicator theme is recommended and reason for ranking	Next steps extensive analytical studies, intensive multi-watershed experiments, adaptive management, or none
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems? (see Figure 5, lines A, B, C, and D)	water quality / chemistry	•N concentration (nitrate, nitrite, ammonia) •P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)	Low	Would provide information on background sources of nutrients.	intensive multi-watershed experiments or adaptive management
	primary productivity	•algal (blue-green algae), macrophyte, and/or phytoplankton biomass •chlorophyll a •diatom biomass (or community diversity)	Low	Most evidence about effects of MD nutrients on ecosystem components (e.g., other trophic levels) is represented by studies demonstrating statistical correlations. Hence, there are cautions when interpreting these results. Experimental manipulations of entire ecosystems are needed to develop defensible and quantifiable relationships that can be used to establish escapement goals. Few studies provide this type of guidance, especially as relevant to BC.	intensive multi-watershed experiments or adaptive management
	secondary productivity	•zooplankton biomass (or community diversity)	Low		intensive multi-watershed experiments or adaptive management
	macroinvertebrate production	•index of biological integrity (IBI) •invertebrate biomass (or community diversity)	Low		intensive multi-watershed experiments or adaptive management
	juvenile fish production (other species and/or salmon life stages)	•salmon smolt abundance •juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) •juvenile weight	Low		intensive multi-watershed experiments or adaptive management
	timing of stock migration	•migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	Low	Also need to better understand influence / importance of spawning timing on freshwater and ecosystem ecosystems.	
	sediment layer	•analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)	Low		intensive multi-watershed experiments or adaptive management
	fine sediment layer	uncertain	Low		intensive multi-watershed experiments or adaptive management

Management questions	Indicator theme	Candidate indicator(s)	Priority high, moderate, low	General comments general thoughts on why indicator theme is recommended and reason for ranking	Next stages extensive analytical studies, intensive multi-watershed experiments, adaptive management, or none
	vegetation	*foliar N and δ15N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) *tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m2/ha/yr])	Low	These indicators cover many different links in Figure 4, as they measure the outcome of several different pathways.	intensive multi-watershed experiments or adaptive management
	riparian insects	* δ15N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	Low		intensive multi-watershed experiments or adaptive management

Part 4: Data Source

Type I Indicators

Management questions	Indicator theme	Candidate indicator(s)	Data source
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	*sea surface temperature (SST) *Pacific Decadal Oscillation (PDO) *El Nino-Southern Oscillation (ENSO) *Coastal Upwelling Indices (CUI) *Oyster Condition Indicator (OCI)	Comprehensive Ocean-Atmosphere Data Set (COADS www.cdc.noaa.gov/coads/) CUI: Pacific Fisheries Environmental Laboratory (PFEL)—http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/upwell_menu_NA.html OCI: (Contact: Steven Hare, International Pacific Halibut Commission)
	harvest rate	*First Nations catch monitoring *commercial catch estimates *recreational harvest	Commercial Fisheries Management—Salmon—DFO Pacific Region (http://www.pac.dfo-mpo.gc.ca/ops/fm/Salmon/default_e.htm), (http://www.pac.dfo-mpo.gc.ca/ops/fm/Commercial/index_e.htm) Recreational Licensing DFO Pacific Region (http://www.pac.dfo-mpo.gc.ca/recfish/Licensing/default_e.htm) DFO's FOS (Fish Operations Systems)—Contact: Bruce A. Patten, Head, Escapement and Fisheries Data Unit, Salmon and Freshwater Ecosystems Division, DFO Pacific Region DFO's MERCI (Management and Evaluation of River Catch and effort Information) system. Available to DFO staff through distributed Access 97 databases. First Nations catch databases, Fraser River—Lower Fraser River (DFO contact Maria Maxwell), BC Interior (DFO contacts: Cindi Yockey, Les Jantz)
	implementation uncertainty	*difference between target and realized harvest rates	Carrie Holt and Randall Peterman (School of Resource and Environmental Management, Simon Fraser University) personal communication
	stock abundance	*abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) *escapement estimates (e.g., NuSEDs)	DFO—NUSeds Database (contact: Erik Grundmann—Regional Data Escarpment Technician)—contains the SIL (Stream Inspection Logs) and SEN (Summary Estimate Narratives); PSCARC Salmon Stock Status Reports (http://www.pac.dfo-mpo.gc.ca/sci/psarc/SSRs/diadromous_ssrs_e.htm) Hydro acoustic test data for target tracking (http://www-sci.pac.dfo-mpo.gc.ca/pbs/english/hydro_a_e.htm), contact: John Holmes—DFO Stock Assessment Pacific Salmon Commission (PSC) In-season Fraser River Escapement Reports (Sockeye and Pink) (http://www.psc.org/info_inseasonfraserescapement.htm)
	enroute mortality (1)	*discharge	Water Survey of Canada (Environment Canada) Real Time Hydrometric Network (http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0) and HYDAT data archive (http://www.wsc.ec.gc.ca/products/main_e.cfm?cname=products_e.cfm) River Forecast Center—MOE (http://www.env.gov.bc.ca/rfc/river_forecast/pilldat.htm)
	enroute mortality (2)	*estimates of enroute mortality *water temperature *disease incidence / virulence	these indicators may be available for certain periods in selected watersheds where current research is underway

Management questions	Indicator theme	Candidate indicator(s)	Data source
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	BC Ministry of Environment—F&W Branch (http://www.env.gov.bc.ca/fw/index.html), GOAT database (http://srmwww.gov.bc.ca/gis/goat5/index.html), Conservation Data Centre (CDC) (http://srmwww.gov.bc.ca/cdc/) Biodiversity Centre for Wildlife Studies; ask Dick Cannings (250 496–4019)

Type II Indicators

Management questions	Indicator theme	Candidate indicator(s)	Data source
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values (see Figure 4, lines A and B)	human disturbance—forestry, agriculture	*area of agricultural activity *watershed area with forest harvesting	BC MOF—Forest Analysis and Inventory Branch (http://www.for.gov.bc.ca/hts/) BC MOE (BC Watersheds Statistics database—Contact: Malcolm Gray, MOE)
	human disturbance—effluent sources	*location of point source discharges	Geo_HRTS (DFO Habitat Referral Tracking System)
	restoration activities	*lake fertilization *stream fertilization *carcass enhancement *forest fertilization	DFO Salmonid Enhancement program (http://www-heb.pac.dfo-mpo.gc.ca/facilities/salmonid_e.htm) DFO—BC MOE Fisheries Project Registry (FPR) (http://www.canbcdw.pac.dfo-mpo.gc.ca/FPR/Qf_frames.asp) DFO Lake Enrichment Program (http://www-heb.pac.dfo-mpo.gc.ca/facilities/lep_e.htm), Contact: Don MacKinlay, DFO (LEP)
	watershed / ecosystem characteristics	*elevation *BEC *stream geomorphology *groundwater *EAU BC	BC MOE (BC Watersheds Statistics Database—contact: Malcolm Gray, MOE) BC MOE Aquifer Classification System (http://www.env.gov.bc.ca/wat/aquifers/index.html) Provincial BEC digital biogeoclimatic subzone/variant mapping (http://www.for.gov.bc.ca/hre/becweb/subsite-map/provdigital-01.htm) Ecological Aquatic Units (EAU) for BC—contact: Kristy Ciruna, Coordinator of Conservation Programs, Nature Conservancy of Canada (NCC)
	hydrology	*discharge *lake flushing rate *annual precipitation *watershed drainage area	Environment Canada, Water Survey of Canada—Real Time Hydrometric Network (http://scitech.pyr.ec.gc.ca/waterweb/formnav.asp?lang=0) and data archives (HYDAT) (http://www.wsc.ec.gc.ca/products/main_e.cfm?cname=products_e.cfm) BC MOE (Watershed Statistics Database—contact: Malcolm Gray, MOE) ClimateSource (http://www.climatesource.com/products.html)
	vegetation cover	*BEC *length of stream with riparian harvesting *riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)	BC MOE (Watershed Statistics Database—contact: Malcolm Gray, MOE)
	bedrock geology	*classification of bedrock geology	BC Ministry of Energy and Mines The MapPlace http://www.em.gov.bc.ca/mining/Geolsurv/mapplace/default.htm
	microbial processing	uncertain	

Management questions	Indicator theme	Candidate indicator(s)	Data source
	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) *acidity (pH), alkalinity *water temperature *Total dissolved solids (TDS)	BC MOE (Fisheries Inventory—BC Lakes Database—http://srmwww.gov.bc.ca/fish/survey_data/index.html) BC MOE Field Data Information System—FDIS (http://www.bcfisheries.gov.bc.ca/fishinv/start.html) Envirodat—The B.C. and Yukon Water Quality Monitoring Network (http://scitech.pyr.ec.gc.ca/climhydro/wq_explanation_e.asp) BC Ministry of Energy, Mines and Petroleum Resources: BCGS GeoScience Map (http://webmap.em.gov.bc.ca/mapplace/minpot/bcgs.cfm)
	spawner abundance (1)	*escapement estimates (e.g., NuSEDs)	DFO—Nosed Database (contact: Erick Grundmann—Regional Data Escarpment Technician); Pacific Salmon Commission (PSC) In-season Fraser River Escapement Reports (Sockeye and Pink) (http://www.psc.org/info_inseasonfraserescapement.htm)
	spawner abundance (2)	*historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	possibly available for certain periods in selected watersheds where current research or project evaluations are underway
	salmon distribution	*fish distribution mapping	MOE's Fish Information Summary System (FISS—http://srmwww.gov.bc.ca/fish/fiss/index.html) BC MOE fish distribution modeling—contact Eric Parkinson, MOE) DFO Spatial Data Holdings and Master GIS data server (http://www-heb.pac.dfo-mpo.gc.ca/maps/datahold_e.htm)
	distribution of predators	*distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	BC Ministry of Environment—F&W Branch (http://www.env.gov.bc.ca/fw/index.html), GOAT database (http://srmwww.gov.bc.ca/gis/goat5/index.html), Conservation Data Centre (CDC) (http://srmwww.gov.bc.ca/cdc/access.html) mammal field guides; The Birds of British Columbia, Volume 2 (Campbell et al. 1990); Coastal Resource Information Management System-CRIMS (http://srmwww.gov.bc.ca/dss/coastal/crimsindex.htm) Community Mapping Network Atlases (http://www.shim.bc.ca/atlases/atlas.html) Coast Information Team (CIT) data; contact: Debbie Narver, Section Head, Resource Information, MOE Nanaimo
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	BC Ministry of Environment—F&W Branch (http://www.env.gov.bc.ca/fw/index.html), GOAT database (http://srmwww.gov.bc.ca/gis/goat5/index.html), Conservation Data Centre (CDC) (http://srmwww.gov.bc.ca/cdc/) Biodiversity Centre for Wildlife Studies; ask Dick Cannings (250 496–4019)

Type III Indicators

Management questions	Indicator theme	Candidate indicator(s)	Data source
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems? (see Figure 5, lines A, B, C, and D)	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)	BC MOE (Fisheries Inventory—BC Lakes Database—http://srmwww.gov.bc.ca/fish/survey_data/index.html) BC MOE Field Data Information System—FDIS (http://www.bcfisheries.gov.bc.ca/fishinv/start.html) (No Suggestions)—The B.C. and Yukon Water Quality Monitoring Network (http://scitech.pyr.ec.gc.ca/climhydro/wq_explanation_e.asp)
	primary productivity	*algal (blue-green algae), macrophyte, and/or phytoplankton biomass *chlorophyll a *diatom biomass (or community diversity)	possibly available for certain periods in selected watersheds where current research is underway
	secondary productivity	*zooplankton biomass (or community diversity)	possibly available for certain periods in selected watersheds where current research is underway
	macroinvertebrate production	*index of biological integrity (IBI) *invertebrate biomass (or community diversity)	Streamkeepers Central Database (http://habitat.pac.dfo.ca/pskf/version4_0/system/skmenu1.cfm) possibly available for certain periods in selected watersheds where current research is underway
	juvenile fish production (other species and/or salmon life stages)	*salmon smolt abundance *juvenile standing stock for other fish species (e.g., rainbow trout, kokanee) *juvenile weight	CNAT (Core Numbers and Traits) DFO database for Okanagan Sockeye production (Contacts: Dr. Kim Hyatt, Margot Stockwell, DFO) possibly available for certain periods in selected watersheds where current research or project evaluations are underway
	timing of stock migration	*migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	Pacific Salmon Commission (PSC) Test Fishery Summaries (http://www.psc.org/info_testfishing.htm) Hydro acoustic test data for target tracking (http://www-sci.pac.dfo-mpo.gc.ca/pbs/english/hydro_a_e.htm), contact: John Holmes—DFO Stock Assessment Pacific Salmon Commission (PSC) In-season Fraser River Escapement Reports (Sockeye and Pink) (http://www.psc.org/info_inseasonfraserescapement.htm)
	sediment layer	*analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)	available for certain periods in selected watersheds where current research is underway e.g., Raincoast Conservation Society's Wild Salmon Project (http://www.raincoast.org/proj-salmon/proj-salmon-5.shtml) e.g., Holtham A., I. Gregory-Eaves1, M. Pellatt, D. Selbie, L.Stewart, B. Finney and J. Smol. 2004.The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (*Oncorhynchus nerka*) nutrient dynamics in Alaska and British Columbia. Journal of Paleolimnology 32: 255–271.
	fine sediment layer	uncertain	

Management questions	Indicator theme	Candidate Indicator(s)	Data source
	vegetation	*foliar N and δ15N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) *tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m2/ha/yr])	available for certain periods in selected watersheds where current research is underway e.g., The Salmon Forest Project (http://web.uvic.ca/~reimlab/salmonforest.html)—Contact: Dr. Tom Riemchen, Department of Biology, U. of Victoria
	riparian insects	* δ15N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	available for certain periods in selected watersheds where current research is underway e.g., The Salmon Forest Project (http://web.uvic.ca/~reimlab/salmonforest.html)—Contact: Dr. Tom Riemchen, Department of Biology, U. of Victoria

Part 5: Data Comments

Type I Indicators

Management questions	Indicator theme	Candidate Indicator(s)	Data Comments *(i.e., Which specific data should be collected or indicators should be quantified?)*
Type I Indicators—Which factors affect changes in spawner abundance? (see Figure 3, x-axis)	marine conditions	•sea surface temperature (SST) •Pacific Decadal Oscillation (PDO) •El Nino-Southern Oscillation (ENSO) •Coastal Upwelling Indices (CUI) •Oyster Condition Indicator (OCI)	Mantua, N., Hare, S., Zhang, Y., Wallace, J., and Francis, R. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. 78: 1069–1080. Hare, S.R. and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47: 103–145.
	harvest rate	•First Nations catch monitoring •commercial catch estimates •recreational harvest	MERCI provides data warehousing and weekly catch statistics for roving and access site creel surveys. MERCI is now an integral part of DFO's management of First Nations chinook and sockeye salmon fisheries on the Fraser River. Notes: distinguish between Pilot Sales fisheries or Economic Opportunities and Food Social and Ceremonial. MERCI databases only catch the latter. Sales fisheries are treated as total census counts, using mandatory landing slips. The FOS (Fishery Operations Systems) is a database and application used by DFO to manage fisheries and document fishery related data (e.g., catch, openings, activity, assigned items). It is predominantly used for the commercial salmon fisheries but there is increasing more use for other fisheries as well.
	implementation uncertainty	•difference between target and realized harvest rates	
	stock abundance	•abundance estimates (pre-season and in-season forecasts, hydroacoustic estimates) •escapement estimates (e.g., NuSEDs)	NuSEDs (DFO's Salmon Escapement Data System) is a central summary database that maintains information on annual estimates of salmon escapement from key river systems in BC. NuSeds SIL (Stream Inspection Logs) contains details about raw fish observations (i.e., viewing conditions stream segment details, observations by stream segment, totals and estimates for the inspection, comments, etc.) The SEN (Summary Estimate Narratives)contains details around a population's annual summary estimate i.e., analysis method, measures of reliability, run timing, estimates broken down by type (e.g., natural adults, broodstock removals, females, etc.). The 2 products can be linked. DFO' s MAPSTER website (http://www-heb.pac.dfo-mpo.gc.ca/maps/maps-data_e.htm) provides access to interactive maps showing the locations of monitored escapement streams and the associated escapement and FISS salmon spawning points and zones, as well as associated DFO escapement reports and data
	enroute mortality (1)	•discharge	The Water Survey of Canada currently operates 2921 active water level and streamflow stations. Data for 1429 of the 2921 active stations are transmitted in near real-time. An additional 5412 hydrometric stations are no longer active, but their data are stored with the active station data in the national HYDAT database. The province's River Forecast Center has data on 1) Snow Water Equivalent pillow data (in millimeters) for the last seven days available in table form (SW.CSV file). 2) Cumulative Precipitation at the pillow site (in millimeters) for the last seven days available in table form (PC.CSV file). 3) Actual Temperature at the pillow site (in degrees Celsius) for the last seven days available in table form (TA.CSV file), and 4) Gauge heights from selected river flow gauges.

Management questions	**Indicator theme**	**Candidate Indicator(s)**	**Data Comments** *(i.e., Which specific data should be collected or indicators should be quantified?)*
	enroute mortality (2)	*estimates of enroute mortality *water temperature *disease incidence / virulence	available for certain periods in selected watersheds where current research is underway e.g., Cooke, S.J., Hinch, S.G., Farrell, A.P., Lapointe, M.F., Jones, S.M.R., Macdonald, J.S., Patterson, D.A., Healey, M.C., & Van Der Kraak, G. (2004). Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia. Fisheries 29:22–33. e.g., Moore, R.D. Stream temperature patterns in British Columbia, Canada, based on routine spot measurements. Canadian Water Resources Journal. (in press).
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	

Type II Indicators

Management questions	**Indicator theme**	**Candidate indicator(s)**	**Data Comments** *(i.e., Which specific data should be collected or indicators should be quantified?)*
Type II Indicators—In which areas will increases in spawner abundance have the greatest influence on other ecosystem values (see Figure 4, lines A and B)	human disturbance—forestry, agriculture	*area of agricultural activity *watershed area with forest harvesting	MOE's BC Watersheds Statistics has summarized existing provincial GIS databases on a watershed basis with results presented either on Excel spreadsheets or on GIS maps. Approximately 150 measurements have been calculated for each watershed. This tool can be used to rank and prioritize watersheds for restoration, to provide baselines for future monitoring, to provide strategic overviews, and to analyze existing watershed conditions for management decision-making. Measurements include: percent of watershed logged; percent logged on steep slopes; percent of remaining old growth forests; road density; kilometres of streams logged to the bank; kilometres of streams with known fish distribution; human uses, etc.
	human disturbance—effluent sources	*location of point source discharges	The HRTS is used by DFO Habitat biologists and administrators across the country to record and track information and actions taken on habitat referrals received either directly from a proponent or indirectly from a provincial or other agency with respect to proposed works or undertakings which may affect fish or habitat. In addition, the HRTS is used as the interface to export data on those environmental assessments (EAs) which trigger the Canadian Environmental Assessment Act (CEAA) to the Federal Environmental Assessment Index (FEAI). All DFO Habitat biologists have access to Geo-HRTS internally via a DFO application portal
	restoration activities	*lake fertilization *stream fertilization *carcass enhancement *forest fertilization	SEP's focus is varied—major hatcheries and spawning channels, fertilization of selected sockeye lakes on Vancouver Island The Fisheries Project Registry (FPR) is a map-enabled database management system, accessible on the Internet, which tracks minimum data about the existence, general nature, location and key contacts for specific categories of fisheries-related projects. These projects include: inventory and biophysical surveys, stock assessment, stewardship, resource planning, restoration and enhancement and economic development.

Management questions	Indicator theme	Candidate indicator(s)	Data Comments *(i.e., Which specific data should be collected or indicators should be quantified?)*
	watershed / ecosystem characteristics	*elevation *BEC *stream geomorphology *groundwater *EAU BC	MOE's Aquifer Classification System has been developed to inventory and prioritize aquifers for planning, management and protection of the Province's ground water resource. To date, over 600 aquifers have been delineated in the province. EAU BC is a spatially explicit, hierarchical, freshwater ecological classification currently in development for BC. EAU BC captures environmental features and processes defining variability in BC's freshwater ecosystems at three spatial scales (ecological drainage units, rivers ecosystems and lake and stream reach ecosystems), similar to that of the biogeoclimatic ecosystem classification (BEC) for terrestrial ecosystems. It is packaged as a digital map and database information system (GIS) so that the classification data (key environmental factors and ecosystem types), can be queried and viewed at multiple spatial scales. Abell, R. A, P.T. Hurley, D. M. Olson, E. Dinerstein. 2000. Freshwater Ecoregions of North America: A Conservation Assessment. ClimateSource serves
	hydrology	*discharge *lake flushing rate *annual precipitation *watershed drainage area	ClimateSource serves up spatial climate data for western Canada, including monthly min/mean/max precipitation and air temperature
	vegetation cover	*BEC *length of stream with riparian harvesting	*riparian vegetation (e.g., presence of nitrogen fixing vegetation—alder)
	bedrock geology	*classification of bedrock geology	
	microbial processing	uncertain	
	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia) *P concentration (TP—total phosphorous, SRP—soluble reactive phosphate) *acidity (pH), alkalinity *water temperature *Total dissolved solids (TDS)	The B.C. and Yukon Water Quality Monitoring Network presently consists of 36 long-term ambient water quality monitoring stations on rivers in British Columbia, and 5 stations on rivers in the Yukon. These stations are primarily operated on rivers of federal interest (e.g., transboundary, national parks, major fisheries). Most sites are sampled on a bi-weekly basis for a wide range of water quality variables, including trace metals, nutrients, major ions, fecal coliforms, and other parameters of site-specific importance (e.g., dissolved oxygen, pesticides, etc.) The data is stored in an Oracle relational database called Envirodat.—contact: Andrea Ryan (Environment Canada) FDIS is a data capture and reporting tool for fish and fish habitat data that has been collected according to Resource Information Standards Committee (RISC) standards. FDIS has been designed so that data files may be uploaded into provincial oracle databases for distribution through various websites. The data is used for many purposes inc
	spawner abundance (1)	*escapement estimates (e.g., NuSEDs)	MAPSTER website (see earlier summary) provides delivery of the NuSEDS data The Pacific Salmon Commission provides daily estimates of in-season gross escapement of Fraser River sockeye and pink salmon moving past Mission (i.e., typically between June and September). These gross escapement numbers represent the total of the number of fish available bcth for catch and for spawning above Mission.
	spawner abundance (2)	*historical abundance estimates (e.g., stock reconstruction by analyzing lake sediment cores or tree-ring data)	

Management questions	Indicator theme	Candidate Indicator(s)	Data Comments *(i.e., Which specific data should be collected or indicators should be quantified?)*
	salmon distribution	*fish distribution mapping	MAPSTER website (see earlier summary) provides delivery of FISS data
	distribution of predators	*distribution of osprey, bald eagle, black bear, grizzly bear, northern river otter	The CDC provides information on the conservation status and locations (occurrences records) of species and ecological communities at risk in BC. The Community Mapping Network website maintains relevant wildlife mapping projects that include; The South Coast Grizzly Bear Monitoring Network, The Wildlife Tree Stewardship Atlas (e.g., bald eagle, osprey, heron nest locations), The Pacific Coastal Resource Atlas and Regional Habitat Atlases. The Coast Information Team (CIT) has assembled the best available scientific, traditional, and local knowledge of fish and wildlife to develop independent information and analyses in support of ecosystem-based management (EBM) in the north and central coastal region of British Columbia,
	abundance of predators	*abundance of osprey, bald eagle, black bear, grizzly bear, northern river otter	

Type III Indicators

Management questions	Indicator theme	Candidate indicator(s)	Data Comments *(i.e., Which specific data should be collected or indicators should be quantified?)*
Type III Indicators—How do changes in spawner abundance influence freshwater, riparian, and terrestrial ecosystems? (see Figure 5, lines A, B, C, and D)	water quality / chemistry	*N concentration (nitrate, nitrite, ammonia)	*P concentration (TP—total phosphorous, SRP—soluble reactive phosphate)
	primary productivity	*algal (blue-green algae), macrophyte, and/or phytoplankton biomass	*chlorophyll a *diatom biomass (or community diversity)
	secondary productivity	*zooplankton biomass (or community diversity)	
	macroinvertebrate production	*index of biological integrity (IBI) *invertebrate biomass (or community diversity)	Macroinvertebrate information is collected by community Streamkeepers, following standardized procedures in StreamNet modules (the central database administered by DFO)
	juvenile fish production (other species and/or salmon life stages)	*salmon smolt abundance *juvenile standing stock for other fish species (e.g., rainbow trout, kokanee)	*juvenile weight
	timing of stock migration	*migration timing information (test fishery data, scale and DNA analysis, hydroacoustic surveys)	Test fishing is undertaken by the Pacific Salmon Commission to assess the fish stocks from specific locations for a particular time. Test fish information may indicate the stock abundance, fish behaviour, species composition, and provide biological samples (scales, tissue, fins, etc.).
	sediment layer	*analysis of lake sediment cores—changes in diatom community diversity and accumulation of nutrients over time (marine-derived and natural sources)	
	fine sediment layer	uncertain	
	vegetation	*foliar N and δ15N of selected species (spruce, devil's club, ferns, willow, poplar, western hemlock, red huckleberry, salmonberry, mosses, liverworts) *tree growth (dendochronology, mean annual basal area growth within 25m of spawning stream, annual growth per unit forest area [m2/ha/yr])	The Salmon Forest Project is using nitrogen and carbon isotopes to quantify the uptake of salmon-derived nutrients by mosses, herbs, shrubs, trees, insects, songbirds, bears and wolves. The project is also focused on the detection of salmon signatures in the yearly growth rings of ancient trees.
	riparian insects	* δ15N of selected insects such as herbivorous and carnivorous carabid beetles (Carabidae)	